Universidade de Aveiro Departamento de Ambiente e Ordenamento
2016

Michael Anthony Martins Tavares Russo

Household water heating using small scale wind turbines

Produção de Águas Quentes Sanitárias (AQS) usando micro aerogeradores

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Dissertation presented to the University of Aveiro required to obtain the degree of Master in Sustainable Energy Systems, made under the supervision of Nelson Amadeu Dias Martins PhD, Auxiliary Professor at the Department of Mechanics of the University of Aveiro.

Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Sistemas Energéticos Sustentáveis, realizada sob a orientação científica do Prof. Doutor Nelson Amadeu Dias Martins, Professor Auxiliar do Departamento de Mecânica da Universidade de Aveiro.

“Learn from yesterday, live for today, hope for tomorrow. The important thing is not to stop questioning.” – Albert Einstein

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keywords wind, solar, power, energy, thermal, renewable, household water heating

abstract

Power consumption is increasing at a global scale and, with it, renewable technologies have been developed at an unprecedented rate to attempt to mitigate the negative effects this has on the environment. In this dissertation the effectiveness of a small wind turbine for the purpose of household water heating is investigated. The aim is to eventually complement or replace the market leading solar collectors in urban areas where solar resources are less than favorable. To achieve these results, climate data for various regions in Portugal were reviewed and, based on their wind and solar resource behavior, Aveiro, Nazaré and Angra do Heroísmo (profiles A, B and C, respectively) were chosen for this study as representative locations.

Daily power output of wind turbines and solar collectors in the three reference conditions was simulated for an entire year using two different modeling approaches (software). Profile A is not recommended for wind applications as the wind power is too low to be considered satisfactory. The other profiles, B and C, show optimistic results and are good locations for the implementation of small wind turbine future technology and currently commercialized systems, respectively. The results show that wind power can achieve a renewable fraction of 40-70% in wind profiles similar to that found in profile C.

Operational and maintenance costs, including grid purchases and levelized costs of energy were calculated for wind and solar power. In profiles A and B, solar power proves to be the most financially viable option. Considering currently available technology and market costs, wind applications should be considered only in profile C, with a payback period of 5 to 7 years. Type B wind profiles may become financially attractive depending on the improvement of wind turbines performance.

A combination of wind and solar power was also analyzed. The available wind and solar radiation prove not to be compatible throughout the hours of the day. However, the yearly profile of these resources in terms of seasonal behavior can make a hybrid system a viable option when combining the wind profile C and solar profile B.

In summary, a cost-effective deployment is possible in profile C and not possible in profile A. As for profile B, the cost of the turbine would have to be lower than what is available under current technology. Nonetheless, with some improvements to the wind turbines, such as cut-in speeds of 1 to 2 m s^{-1} and a decrease in cost of 30-40% locations with this profile can be considered as viable options in the future.

palavras-chave vento, sol, energia, potência, térmico, renovável, Águas Quentes Sanitárias (AQS)

resumo

O consumo energético global está em constante crescimento, e com este aumento as tecnologias renováveis têm sido desenvolvidas a um ritmo sem precedentes para mitigar os efeitos negativos que este consumo tem no ambiente. Nesta dissertação é investigada a viabilidade de usar micro aerogeradores com o propósito de produzir Águas Quentes Sanitárias (AQS). O objetivo é eventualmente substituir os coletores solares térmicos em zonas urbanas onde o recurso solar é menos favorável, ou complementá-los de modo a aumentar a cobertura das necessidades por fontes renováveis. Para obter estes resultados, foram avaliados dados climáticos de várias regiões de Portugal, e devido ao seu perfil de vento e sol, Aveiro, Nazaré e Angra do Heroísmo foram as escolhidas para neste estudo representar 3 perfis de referência no que respeita a potencial renovável (perfil A, B e C, respetivamente).

Foi simulada a energia gerada por micro aerogeradores e coletores solares durante o período de um ano, em dois programas de modelação diferentes. Conclui-se que a implementação de um sistema micro eólico numa região com um perfil de vento como o perfil A não é recomendada, sendo que a potência gerada não seria considerada satisfatória. Para os perfis B e C, estes mostram resultados mais otimistas correspondendo a perfis de vento suficientemente interessantes para justificar a implementação de tecnologia eólica no seu estado de desenvolvimento presente (no caso do perfil C) e eventualmente no futuro (no caso do perfil B). Os melhores resultados mostram uma fração renovável de 40-70%, em perfis de vento tipo C.

Foram calculados os custos de operação e manutenção, incluindo compras à rede elétrica, e os custos da energia eólica e solar. Em locais com perfis de vento comparáveis a Aveiro ou a Nazaré (perfis tipo A e B), a energia solar térmica é atualmente a opção economicamente mais viável. No estado atual de desenvolvimento da tecnologia, as soluções baseadas em micro turbinas eólicas devem apenas ser consideradas para locais com perfis de vento idênticos ou superiores aos encontrados em Angra do Heroísmo, tendo um período de retorno do investimento de 5 a 7 anos.

A combinação de eólica e solar foi também estudada. Concluiu-se que para um sistema híbrido não se comprova uma combinação favorável entre os recursos eólicos e solares ao longo do dia. No entanto, o perfil anual dos recursos é complementar para situações onde se encontra um perfil de vento tipo C e um perfil solar tipo B.

Resumindo, implementação desta tecnologia para o perfil C é possível, mas não o é para o perfil A. No caso do perfil B, com alguns melhoramentos das turbinas eólicas, como a diminuição da velocidade de cut-in para valores entre 1 e 2 m s^{-1} e a diminuição do custo em 30-40%, localidades com este perfil podem ser viáveis no futuro.

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Chapter 1 - Introduction

1.1 Contextualization

In a society with an ever increasing energy demand [1,2], it is key that we strive for a more sustainable future. The work developed by the scientific community has now made the world take a closer look at renewable energy and energy efficiency and understand that these are key to addressing future problems. Thus, as global energy demand increases, the awareness of how energy consumption affects the environment has also increased.

In 2014, approximately half of the final global energy consumption was for heating systems. Although this sector has been a major target of new developments in the renewable energy market, renewables account for only 8% of the energy production for such purposes. In this sector this value is very low, but in 2015 new renewable energy, used as power sources, increased almost 59% from the previous year. This means that global energy production from renewables is now up to 22.8%, with wind, solar and hydro dominating the market and increasing in all regions [2].

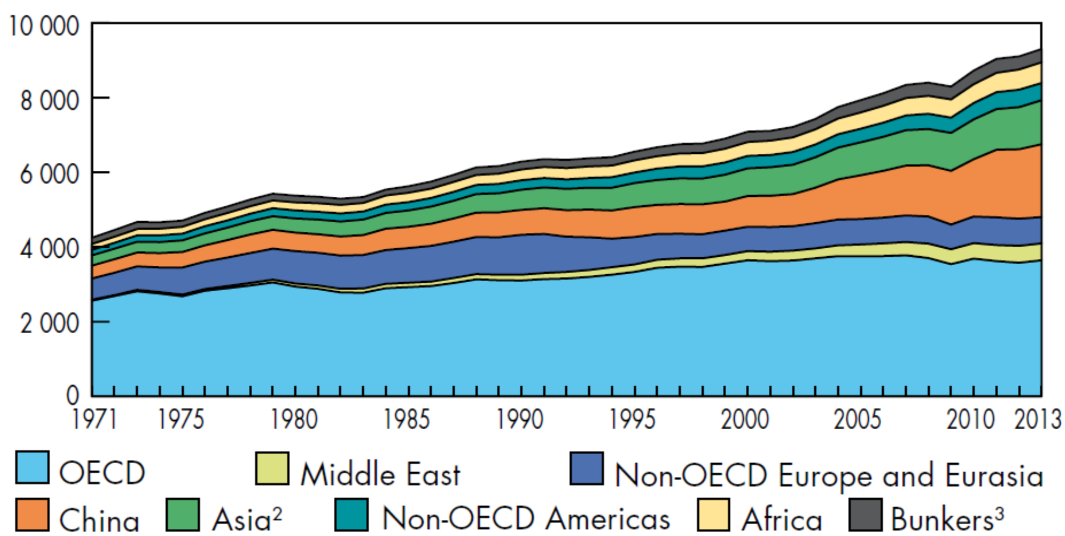

Figure 1a - World energy consumption by region (1971 to 2013) [1]

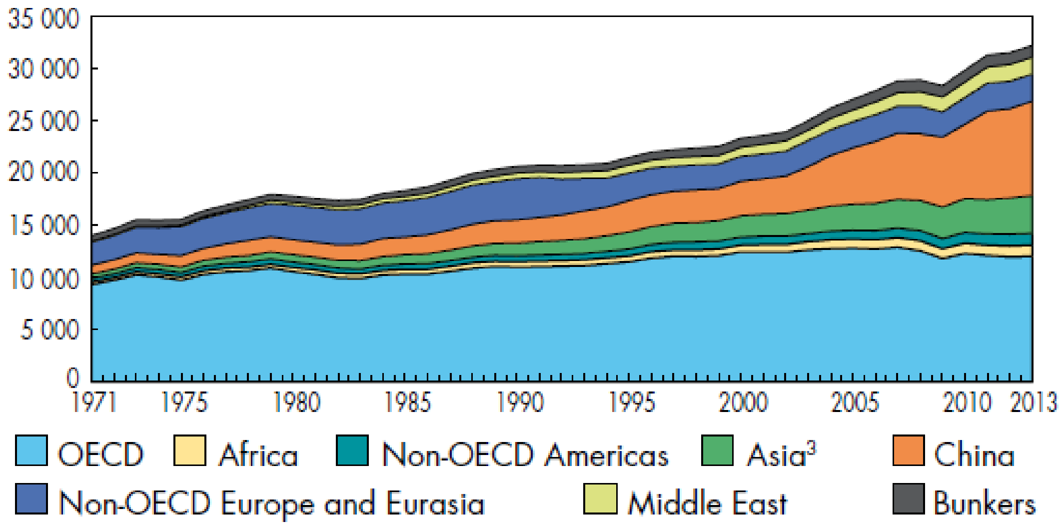

Figure 1b - World CO2 emission by region (1971 to 2013) [1]

Despite this, as seen in Figure 1a and 1b, energy consumption and CO_2 emissions are forecast to increase over the next decades, most notably in Asia. Taking China as an example, the country has had an exponential economical and industrial growth and consequently has been increasing their pollutant emissions at an alarming rate.

Even with an increase in renewable energy investment, the issues with air pollution in China have not improved and are one of the top priorities of the environmental force of the country [3], with China being one of the 164 countries that had defined renewable energy targets by 2015 [2]. However, the environmental impact that has been suffered so far will be hard to revert while the country is still in development.

In sum, all the data point to a future where there is still a struggle against pollutant emissions and energy consumption. An increase in environmental impact awareness and investment in renewable energy represents the only viable path to a sustainable future. But with this future comes a greater challenge, renewable resources, like solar or wind, cannot generate energy at a steady pace. When the behavior of the resource we are trying to use is unpredictable the only viable solution is to simulate when the resource will be available and have different systems in place that can use it accordingly.

1.2 General Objectives

The objective of this manuscript is to study the behavior of a conventional, low cost, small horizontal axis wind turbine (HAWT) for a water heating production system in an urban scenario that is also connected to the grid. This system, depending on the location, can also have a solar thermal component. Simulations will be carried out to predict the behavior of the available resources and to analyze the feasibility of the system. The results from the simulation will be used for comparison between various wind and solar profiles, allowing not only the comparison of efficiency of the system for the intended purpose and availability of the resource, but also make a financial assessment of the cost of implementation and maintenance of the system. Being viable, this system could help renewable energy further enter the household energy market and the possibility of implementation of water heating systems in regions where there is less solar availability and a good wind profile.

1.3 Bibliographic revision

1.3.1 Urban energy generation

Urban energy production at a small scale, or micro-generation [4], allows users to generate energy for on-site use. The most commonly used systems are micro-combined heat and power (cogeneration), solar thermal, photovoltaic, fuel cells, micro-hydro and small (or micro) wind [5]. These systems allow for some degree of freedom when managing a private energy system, but this freedom comes with dealing with the intermittent nature of renewable energy sources, as the natural resource may not always be available.

1.3.2 Hybrid energy systems

When generating energy from a number of different sources for the same goal, such as using wind power and solar thermal energy to heat water, it is called a hybrid system [6]. These systems are comprised of various energy production units that communicate with each other to provide the most efficient way of reaching their goal, be it heating water or generating power. For example, when there no sunlight or the solar resource is lower, a hybrid wind-solar system will use only the wind turbine for power. Alternatively, if the location of the installation is in a sunny region, the wind turbine could be used only to maintain the temperature of the water during the night and when the solar conditions are less than favorable.

1.3.3 Urban wind power

Urban wind power, also known as small wind, consists of a small scale wind turbine that is implemented on or near buildings for energy production purposes with a rated power up to 10 kW. There are a few obstacles to the construction and operation of small wind at this scale, such as the positioning and the actual design of the wind turbine. On the one hand, it is hard to correctly determine where to place the turbine for maximum efficiency due to the interference of the surrounding buildings, and with different heights the turbine output will be significantly affected. On the other hand, designing a wind turbine that will not visually contrast with its surroundings is also a challenge. The positioning can be easily solved if the wind turbine is placed at the top of the highest building, this way the turbine is considered to have full exposure to the available wind. However, this might not be the case, therefore simulating the surroundings of the turbine is the only viable solution. Even if the perfect placement is found, the design will always be one of the factors that most changes public perception of the technology, it must be visually appealing but still be functional. This balance is hard to achieve since most conventional wind turbines have a practical design in consideration and the decorative design falls to the background. The disadvantage of using a system such as this is that reliable and constant wind is very hard to achieve in most cities, even with perfect placement of the wind turbine. Despite this, unlike large turbines, small scale wind turbines have a reduced impact on the environment, they produce much less sound pollution, have no effect on local climate conditions and can commonly start energy production at lower wind speeds [7,8]. New technology is constantly being developed to mitigate some of the issues with urban wind power. While some try to incorporate visual design and function, others approach the issue from a more technical view by building more compact, but still efficient, turbines with lower cut-in speeds or that harvest the wind in new ways [8,9,10]. Vertical axis wind turbines (VAWTs) are another option for, usually, lower cut-in speeds and higher efficiencies, and a higher visual appeal (Figure 2). Also, these types of turbines are omnidirectional, which is an advantage in an urban scenario. However, their cost is higher compared to HAWTs, which make VAWTs a less favorable option when considering a cost-effective system.

Figure 2 - Example of urban wind turbines (goo.gl/Z47KrT)

Since the intermittent nature of the resource availability of renewable energy cannot be controlled, then the most effective way to mitigate this is by improving the design and researching the best locations where this technology can be implemented. This being said, an argument can be made in favor of hybrid systems. These systems, as a whole, can compensate for the lack of resource availability when there is no available power to be extracted from the wind [4,5].

1.3.4 Solar water heating

One of the most commonly used methods of renewable water heating is using a solar thermal collector (Figure 3) [12]. These can be seen in multiple households, both in urban districts as well as in rural areas.

Figure 3 - Solar heat collector for water heating (goo.gl/SjMVjO)

The base concept of a solar thermal collector involves heat transfer and water running in the tubing of the system. The radiation from the sun is harvested and transferred to the water, then the water passes through a water tank and transfers that heat to the water in the tank.

In recent years, the technology for solar water heating has not significantly advanced, however, there has been a new development involving graphene multilayers. These layers try to simulate nanostructure profiles found in moth-eyes which allow the graphene to behave as a blackbody reaching 99% light absorption (from mid-infrared to ultraviolet) [13]. Ultimately, the real world applications for new advances such as this are currently far from being viable. Small-scale development is done under controlled conditions and it is impossible to know how they would behave if applied at a larger scale.

Even with the few technological advances, the global installed capacity of solar renewable energy has been steadily increasing, mainly in China and Japan, with China alone accounting for 80% of the global solar collectors. Solar thermal collectors can be implemented in a wide variety of environments, and there has been an increase in their use in large scale applications such as hotels, schools and district heating [2]. The increase in the number of solar panel applications is a healthy sign for the renewable energy market, however, only by further developing the technology, or implementing hybrid systems, can the problems with solar availability be minimized so that the market can grow.

1.3.5 Net-Zero Energy Building (NZEBs) and Zero Energy Building (ZEBs)

Although there are many definitions of what constitutes a NZEB and a ZEB, both are considered to be the future of building design. ZEBs generate energy for on-site consumption and are autonomous, which is to say that the total annual energy production is equal or greater to the total energy consumption. NZEBs function on the same principal than ZEBs but are connected to the grid and use the grid as an energy storage device, meaning that all the energy produced is injected to the grid and energy is consumed from the grid, with the net energy being zero (energy injected to the grid = energy used from the grid) (Figure 4).

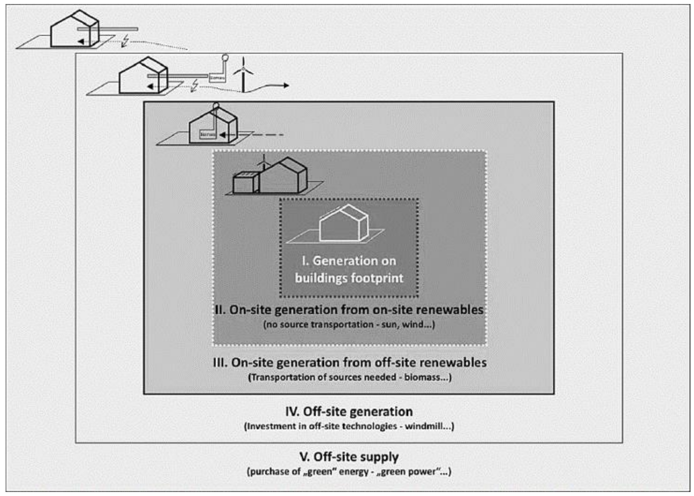

Figure 4 - Zero Energy Building (ZEB) renewable supply options [9]

The only variation of these definitions is the use of “net energy” in ecological economics which encompasses the lifetime of the installed equipment and their use [14].

The goal is for new buildings have on-site and/or off-site renewable energy generation and strive for a nearly zero energy building, with each country having their own guidelines to accomplish this. Reaching this design is not an easy task, managing the energy production systems and on-site energy consumption, so that the net balance is “zero”, is a complicated and yet to be standardized method. However, in some cases there can be several buildings connected to the grid and be as a whole, a zero energy group [15]. Finally, from a technological standpoint, current renewable energy systems are sufficient to reach the nearly-zero energy buildings at least until the 2021 guidelines [16]. However, some advances have been made in the energy storage market, more specifically household batteries or other storage solutions, to mitigate the intermittent nature of renewable energy sources. Furthermore, the current guidelines for building efficiency certifications demand that new buildings have a minimum energy efficiency rating, which is an additional incentive to install renewable energy generators.

1.3.6 Simulation

When designing a new system it is important to evaluate its performance prior to implementation by trying to simulate the real world behavior of the resource and the system at the installation site [17]. There are many software tools that are able, to some degree, accurately simulate these systems, however, for the purpose of this manuscript the focus will be on HOMER Energy and on System Advisory Model (SAM). Post-analysis can be made in Matlab or Excel, or a combination of both, depending on the amount and complexity of the data. All the tools needed to simulate these systems are available to the general public and, although they require a lot of work to use and manipulate, this process will always be essential for these types of technologies (for other examples of modeling and simulations used for wind power analysis, see [18,19]).

1.3.7 Intermittency and energy storage

Renewable energy production is, at its core, dependent on the available resource. In the case of wind and solar energy, the resource cannot be controlled and this presents a challenge that must be overcome in the coming years. Energy storage technologies play a crucial role in mitigating this issue and can prove to be one of the best solutions for controlling the energy output of a renewable system. The energy storage market is constantly evolving due in part to the transportation industry, alternative solutions for power and batteries eventually bleed into other markets such as housing and quality of life. Today, the most common forms of energy storage are Lithium-Ion batteries. They currently power most of our mobile devices and are now used as energy storage in households, with one of these batteries already being made available by Tesla (American automotive and energy storage company). Although batteries are the first option for many, the problem can be approached from a different perspective. The storage of energy in its final form, such as hot water in secondary water tanks, has the potential to be a cost-effective alternative solution [20].

1.4 State of the art

Although renewable energy is growing in the power generation scenario, it is still a small share of the final global energy used for heating. Development in renewable-powered heating systems is slow when compared to renewables used for electricity, and so they fall to the background since the scale of the latter is much larger than the former. But this might no longer be the case. There has been significant cost reduction in the solar and wind power technology market which allows for a larger range of accessibility. With the possibility that, in the near future, low-cost renewable energy systems reach the marketplace. Making a wind turbine focused only on water heating could potentially be cheaper than those that currently exist. Nevertheless, the main issue with these renewable systems still persists. There is no possible way to guarantee a constant supply of the renewable resource. Hybrid systems and energy storage have the potential to mitigate these issues, however, this will only come to fruition if the global market follows these trends. As for using small wind for heating, there is an enormous market gap, the concept is not widely implemented or studied, which leads to a misplaced distrust of its capabilities.

1.5 Research questions

This manuscript will strive to answer the following questions:

- Is a small wind, water heating system, energetically and financially viable when compared to the most commonly implemented technology for this purpose? Namely, solar thermal.
- Can this system operate on its own, or is it necessary to implement a hybrid system?
- If it is not viable, what can be improved?

1.6 Structure and methodology

- System description and methodology;
- Power and financial results;
- Results analysis and discussion;
- Goals for the future of wind technology;
- Conclusion.

Chapter 2 - System Description & Simulation Methodology

2.1 Chapter summary

This chapter is dedicated to providing a description of the hybrid renewable energy system and its components, as well as depicting the simulation methodology which includes the case study locations, the data used for the simulation and the simulation process itself. The goal of the system is to be as simple and economical as possible, with low maintenance and operational costs and a high heating efficiency.

2.2 Key system components

For both wind and solar power, the system is connected to the energy grid which acts as a backup generator to compensate the intermittency of the resources. The components are as follows: wind turbine, solar thermal collector, inverter (optional), heating elements and water tank (Figure 5). Heat transfer to the water in the tank occurs by the heating elements inside (joule effect), which is connected to the wind turbine and the energy grid, and by the tubing from the solar collector. The entire system is projected to have the components in close proximity to mitigate the power transmission loss. These losses can occur either in the form of heat from the tubing of the solar collector or the electricity in the cables of the wind turbine and energy grid.

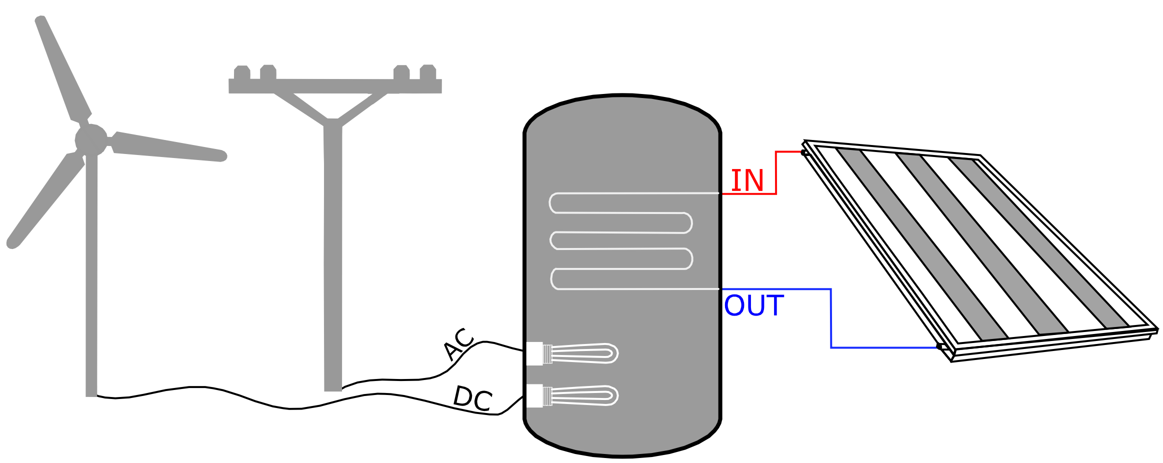

Figure 5 - Main system components and connections

2.2.1 Wind turbine

The turbines used in this study are representative of the most economical options available in the current market, therefore, no specific brand was chosen. Furthermore, the power curve of the wind turbines used for the study have an entry level efficiency, meaning that most of the commercialized turbine options, except the low cost versions manufactured with subpar materials, are more efficient than what is used in this manuscript. The power output of each turbine (1kW, 2kW and 3kW) was chosen based on the system sizing, energy and their cost. Both horizontal and vertical axis turbines can be approximated by the generic power curves that were created for this study. As for the rest of the system, the wind turbine is connected to the DC water heating element in the main tank. Depending on the existence of secondary water tanks, for the purpose of energy storage, there is a need for additional heating elements connected to the wind turbine (one per tank).

2.2.2 Solar collector

The solar thermal collectors used in this study have an output energy of 1kW, 2kW and 3kW, with characteristics according to the industry standards. The panels are identical and the rated power is changed solely on the number of panels that are modeled. The collectors are connected to the water tank solely by the tubing of the panel and are connected to a single tank.

2.2.3 Water tank and energy storage

The main storage component is a water tank. The excess energy that is generated from the system can also be stored in secondary water tanks acting as a battery (this possibility will be studied later in the manuscript). Actual batteries could also be used but since the purpose of the system is to only produce hot water it can be simplified and the energy can be stored directly as hot water. Furthermore, by storing energy in this form it can then be used at a later time without having any additional losses or energy costs, allowing the system to be as independent from the grid as possible.

2.2.4 Heating element and tubing

There are two main types of heating elements, AC or DC current. In this case the heating element can be connected to the wind turbine as well as to the energy grid. However, in doing so, it is necessary to have an inverter installed on the connection between the wind turbine and the heating element, because the output of the wind turbine is DC current. Despite this, another configuration is possible. If two heating elements are implemented, one AC and another DC, an inverter is no longer a necessity, however, this option involves the purchase of a second heating element. The investment needed for the inverter requires more capital, therefore the overall investment with two heating elements would be lower. As for the solar system, it has its own tubing to heat the water therefore it does not directly interact with the heating element.

2.2.5 Control system

Although a control system will not be modeled it is still an important factor to mention. A control system is needed so that components can communicate with each other and decide what tank is heated and at what time [21]–[23]. For example, if there is sufficient energy being produced from the solar collector to heat the water in the primary tank, the wind turbine can begin to heat the secondary tank to start the energy storage process. This system can also be used to monitor the tank and flow conditions and even add a wireless controller so that a system such as this can be used in smart house projects.

2.3 Simulation methodology

2.3.1 System sizing and heating demand

The amount of power required to heat the assumed volume of hot water used per day was calculated using Eq. (1). The considered volume of water is 200 L at 60 ºC (for reference, in Portugal, each person uses on average 40 L of hot water at 60 ºC each day [24]). Furthermore, the efficiency analysis of the proposed system is assuming that the 200 L are used each day of the year, and then evaluating how the system performs based on the grid purchases to fulfill the energy demand.

$$P = \frac{m \times cp \times \partial T}{3600} \quad (1)$$

Where P is the required power to heat the water in $kWh{\cdot}day^{-1}$, m is the mass of the water in the tank that is going to be heated (which is the mass of 200 L in kg), cp is the specific heat of the water (4.184 $J{\cdot}kg^{-1}{\cdot}K^{-1}$) and ∂T is the temperature difference between the inlet water and the desired temperature (45 K).

The following equation gives the total amount of energy required to heat the desired water each day:

$$P = \frac{200 \times 4.184 \times 45}{3600} = 10.46 \frac{\text{kWh}}{\text{day}} \quad (2)$$

Taking this into account, the value used for the energy demand in the simulations was increased by 5% to account for any possible losses that may occur in the system, therefore the total daily energy required is approximately 11 kWh, which translates to an annual demand of 4015 $kWh{\cdot}year^{-1}$.

2.3.2 Case study locations and resource availability

The case study locations were selected based on their wind and solar profile and the behavior of these resources. After reviewing the data for several locations, Aveiro, Nazaré and Angra do Heroísmo were the chosen locations (Figure 6). In terms of solar energy, Portugal as a whole is in an advantageous location, the amount of solar radiation in the country is much higher than most of Europe. Because of this, in any part of Portugal, solar applications are generally viable. With this in mind, the selection for the case studies had to be chosen based mostly on the wind profile. Nevertheless, Angra do Heroísmo has the least amount of available solar radiation of the three, while Aveiro and Nazaré are quite similar. Aveiro has low wind speeds overall and this location represents the minimum wind speeds for a wind application with current technology, however, these speeds are constant during the entire year. Nazaré has medium wind speed averages, even so, it was chosen because this location presents an interesting wind profile, there is an increase of wind speed in the winter as well as in the summer. Finally, Angra do Heroísmo is where high wind speeds can be found, and unlike the others, the wind behaves has expected from most locations, higher wind speeds in the winter and lower wind speeds in the summer.

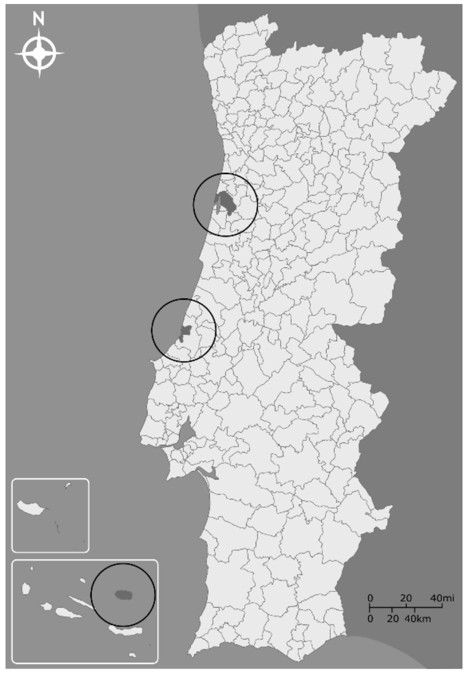

Figure 6 - Study profiles sites (from top to bottom: Aveiro, Nazaré and Angra do Heroísmo).

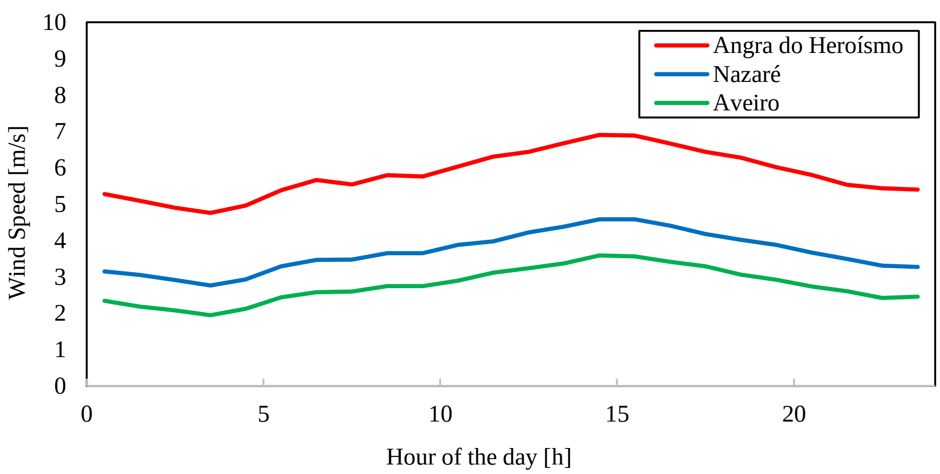

Figure 7 - Annual average hourly wind speeds for the study locations.

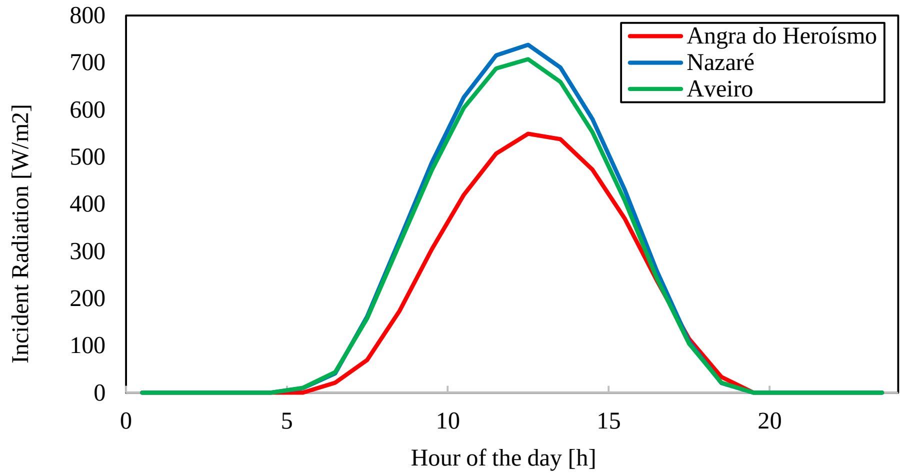

Figure 8 - Annual average hourly incident solar radiation for the study locations.

This study aims to compare different wind and solar profiles and not specifically these three locations. Therefore, during the study, the locations will be referred to as: profile A (actually corresponding to Aveiro, but representing an Aveiro like condition, represented by the color green), profile B (actually corresponding to Nazaré, but representing a Nazaré like condition, with the color blue) and profile C (actually corresponding to Angra do Heroísmo, but representing an Angra do Heroísmo like condition, in red). There were no locations chosen or reviewed that had a large amount of average wind speeds below 2.5 m·s^{-1}, as this wind speed is the most common cut-in speed for conventional wind turbines.

2.3.3 System Advisor Model (SAM) and HOMER Energy Legacy

Simulations were carried out in SAM and HOMER. Both are typically used for power management and financial evolution of energy systems. Each of the software has a similar approach to how the simulation is carried out. The input values for the measured data are presented in hourly averages for the entire year and each model uses the same fundamental principles when calculating power output. The main difference regarding the models is that HOMER does not have the option to simulate a solar thermal collector, only a photovoltaic solar panel. Therefore, HOMER was used only for the purpose of simulating the wind turbines and SAM was used for both wind and solar power.

For the wind data, HOMER allows for the input of monthly averages as well as hourly averages, however, this is not recommended. The input of monthly averages method is not inherently wrong, although in some cases it will lead to miscalculations of the yearly power output. This effect is more notable in the simulation of wind turbines, since they have a non-linear power curve, lower wind speeds generate much less energy than high wind speeds, as will be demonstrated later in the document (Subchapter 2.3.5). Both models were used under the same data, so that there would be more results for comparisons and simulations from one model could validate the other.

2.3.4 Meteorological data

The data used for the models was obtained from the CLIMAS-SCE Excel file made by the National Laboratory of Energy and Geology (LNEG) with data provided by the Portuguese Institute of Sea and Atmosphere (IPMA) from 1971 to the year 2000. SAM can read the EPW file that is exported from CLIMAS-SCE for solar data, yet a wind specific file, an SRW file, was created so that the model could read the wind speed speeds for each location. As for the HOMER model, the hourly data can be imported using a simple TXT. The data was treated to a statistical analysis so that it would be consistent across every region and is organized in hourly averages of temperature, humidity, wind speed, wind direction and solar radiation in all its components. Some wind speeds were not measured in a rectangular grid, so to obtain accurate data for the region the missing values were calculated by spatial interpolation [25]. After the data was gathered for the intended study locations a further analysis was conducted. Average wind speeds and solar insolation were calculated and then compared to the data stored in the Atmospheric Science Data Center at the NASA Langley Research Center [26], and no inconsistencies were found in the overall averages. However, there is a significant flaw in the data provided by LNEG. There are days where the average value of wind speed for each hour of the day is equal to 0, and this occurs for a time period of exactly 24 hours, thus, indicating a lack of data for these days. Further analysis indicated that for the data sets corresponding to Aveiro, Nazaré and Angra do Heroísmo there is missing data for 65, 64 and 62 days, respectively. To overcome this issue, the average wind speed of each month was calculated and the hourly data for each of the missing days was replaced by the average value of wind speed for their respective month. This method allows for the availability of the missing data and a complete dataset to be studied and, although this change affects the average wind speeds of each month, the overall wind profile remains mostly unaltered.

Table 1 shows the monthly averages before and after the change for the location of Aveiro, as well as the impact the new values have in relation to the incomplete data. The new dataset can be used without any consequence since what is being studied is the system and how it behaves throughout the year and not the accuracy of the climate data. Ultimately, in this study, the focus was given to introducing consistent and complete data to the simulation model.

Table 1 - Original and altered monthly wind speed averages, and the impact of the changes on the average wind speed (%), for Aveiro (other locations in appendix 1).

Month	**Original Averages [m/s]**	**New Averages [m/s]**	**Aveiro Difference [%]**
January	2.91	3.20	9.82
February	2.30	2.87	24.96
March	2.39	3.00	25.69
April	2.43	2.92	20.07
May	2.63	2.89	9.86
June	2.03	2.57	26.48
July	2.29	2.66	16.24
August	2.25	2.54	12.77
September	2.04	2.38	16.88
October	2.03	2.49	22.55
November	2.12	2.48	16.82
December	2.84	3.21	12.93

2.3.5 Wind data and calculations

The base calculations for the wind turbine power output is the same for both models. The hourly averages are directly compared to the power curve of the turbine and the power output is registered. The hub height and power law coefficient (HOMER), or shear coefficient (SAM), variables are then taken into account to adjust the power output accordingly. The power law and shear coefficient are the same variable, "α" in Eq. (3), only addressed differently in each model.

$$v\mathrm{hub} = v\mathrm{data} \times \left(\frac{\mathrm{zhub}}{z\mathrm{data}}\right)^{sc} \tag{3}$$

Where v_{hub} is the wind speed at hub height in $m{\cdot}s^{-1}$, v_{data} is the wind speed at measured data height in $m{\cdot}s^{-1}$, z_{hub} is the hub height in meters, z_{data} is the height at which the data was measured in meters and *sc* is the shear coefficient.

Knowing how the models calculate the power output, to quickly illustrate the above mentioned effect regarding the monthly averages and incorrect calculations, consider the following example. Taking into account the power curve for the 3kW wind turbine (Figure 9, this effect is more noticeable with higher power curves), and considering an extreme case example such as: (scenario 1) one month with an average wind speed of 5 $m \cdot s^{-1}$ (each day), and (scenario 2) one month with the same average speed but divided into two sections, for 15 days the wind speed is 0 m/s and for the other 15 days the wind speed is 10 $m \cdot s^{-1}$. In scenario (1) the power output of that entire month would be approximately 180 kWh. In contrast, for scenario (2), the total power output that month would be 810 kWh (Table 2).

Table 2 - Summary of example scenarios (1) and (2).

Scenario (1) [total power = 180 kWh/month]		Scenario (2) [total power = 810 kWh/month]	
Average of 5 m/s (30 days) wind		Average of 0 m/s (15 days) and 10 m/s (15 days) wind	
Speed (m/s)	Turbine Output (kW)	Speed (m/s)	Turbine Output (kW)
5	0.25	0	0
		10	2

In most locations the variability of wind speeds will not be as extreme as stated in this example, nonetheless, when modeling the implementation of a wind turbine, calculations with hourly averages is advised as this will allow for a more accurate representation of the power output of the wind turbine.

Despite this, if one chooses to use monthly averages in HOMER there are additional variables to mitigate this issue. An autocorrelation factor and the diurnal pattern strength. These values tell the program how strongly the wind in one hour depends on the wind in the previous one and how the wind depends on the time of day, respectively. As well as the hour of the day when peak wind speeds are observed and the Weibull “k” variable, also known as the wind shape parameter which mainly describes the amount of wind that a certain location has.

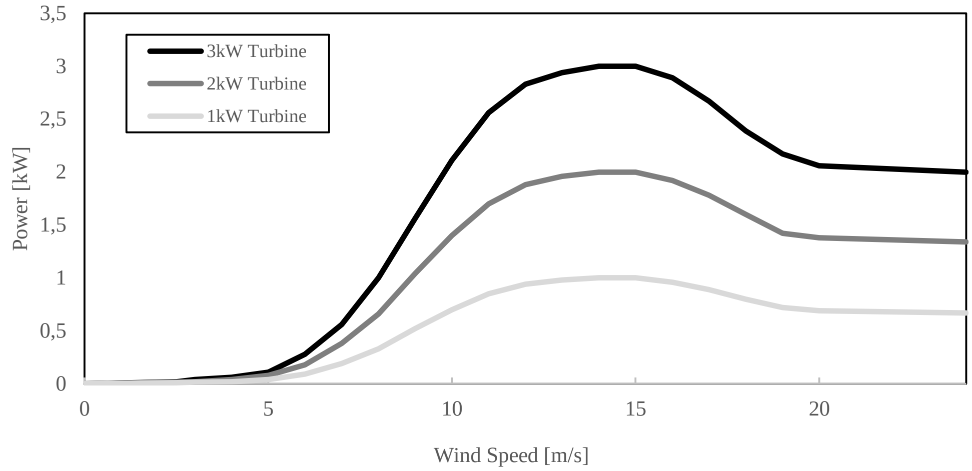

Figure 9 - Wind turbine power curves as a function of wind speed (1kW, 2kW and 3kW).

2.3.6 Solar data and calculations

Solar data for the SAM model is organized in hourly averages, furthermore, the solar data provided by the LNEG CLIMAS-SCE file has hourly solar means that are decomposed in each of the solar beams components. The power output for the solar collector modeled in SAM utilizes the Hottel-Whiller-Bliss method, Eq. (4), which allows for the calculation of the total amount of useful heat collected by the thermal collector panel [27]–[31].

$$Q_u = Fr \times A_{\mathrm{C}} \times [(\tau\alpha)_{\mathrm{e}} \times I - U_{\mathrm{L}}(T_{\mathrm{f}} - T_{\mathrm{a}})] \quad (4)$$

Where Q_u is the useful heat in $W{\cdot}m^{-2}$, Fr the effectiveness of the heat transfer between the collector and the heat removal fluid, A_c the absorber area in m^2, $(\tau\alpha)_e{\cdot}I$ is the energy absorbed by the collector in $W{\cdot}m^{-2}$ and $U_L{\cdot}(T_f - T_a)$ is the collector heat loss $W{\cdot}m^{-2.o}C^{-1}$.

2.3.7 Wind turbine and solar collector simulation

Three models of generic wind turbines were created for this study. Each one presented a different rated powers (1kW, 2kW and 3kW) but with identical power curves so as to minimize the difference between their individual behaviors. Both models used the same power curves for the wind power simulations so that the output, even if not identical due to differences in wind speed input data, would be consistent. Considering an urban scenario, the wind turbine was modeled standing at a height of 15 meters and the interference of the surroundings is taken into account when possible. For the solar collector, the system was sized to have the same rated power than the wind turbines (1kW, 2kW and 3kW), to allow for a more direct comparison between the components. The solar thermal collectors used have the standard characteristics as described in the regulation for energy efficiency in housing [32]. Both system have an assumed lifetime of 20 years.

For the financial analysis the operation and maintenance (O&M) costs are different for solar collectors and wind turbines. The overall maintenance costs of a solar collector are approximately 1% of the initial investment, and for the wind turbine it is accepted that the costs stand at 35 €$\cdot$year^{-1} for small wind (< 10 kW installed capacity). As for the operational costs this value also varies depending on the system. The operational costs can be approximated using Eq. (5), more power generated by the system equals a lower operational cost each year. This value can easily be achieved by verifying a statement that decides if the energy production is enough to satisfy the daily demand. If the statement is true, then that day has no grid purchases and therefore no cost to the consumer. However, if the statement is false, the energy production was insufficient and the cost of the grid purchases and that day is equal to the remaining energy required multiplied by the current market average energy price.

$$OC = (E_d - E_g) \times E_c \tag{5}$$

Where OC is the operational costs in €, (E_d - E_g) is the energy demand subtracted by the energy generated for each day when the generation does not meet the demand, and E_c is the price of energy from the grid in €$\cdot$kWh^{-1}.

2.3.8 Model input data

Table 3 shows the input variables chosen to perform the wind and solar simulations. These variables are either the default value or were attributed according to the average values for some manufacturers. As for the simulation input data itself, starting with the wind turbines, there is either an existing power curve available for the calculations, which is what was used for this study, or by using SAM, there are a few variables that can be added and the program builds the power curve. The most helpful variable used in the models is the wind shear coefficient. This is a value that tells the program what kind of environment the wind turbine is in and how the surroundings interfere with the wind speed at different heights above the ground at the turbine installation site. This value was set at 0.3 which represents an average value for an urban scenario that may include houses and tall buildings similar to the locations used in this study [33]–[37].

For solar collectors, the rated power is not directly chosen but can still be considered an input, depending on the efficiency, losses and area of the collector. The program calculates a rated power and the user can change the area of the panel to adjust the power of the solar thermal collector to the desired value. This value is very useful for this study as it allows for a more direct comparison between the wind turbine and the solar collector, as previously mentioned.

Looking at the initial investment for each technology, the average value of installed solar thermal power is approximately 1200 € for the entire system with a power of 1kW, with an investment of around 800 € for each additional kW, while the mean values for a wind turbine system are of around 1350 €, with an additional cost per kW of 1000 €.

Although these values are not a complete representation of the global solar and wind market, due in part to the large variety of manufacturers, and different materials used, they do represent a good assessment of the amount of capital investment it is needed to implement these technologies in Portugal (which may also include importing material from other EU countries, namely Spain, Germany and the UK) [38].

Table 3 - SAM and HOMER input variables.

SAM Model (Wind)

Input	Value
Rated Power [kW]	[1; 2; 3]
Turbine Power Curve	✓
Hourly wind speed averages [m/s]	✓
Rotor Diameter [m]	[2.5; 3; 3.5]
Hub Height [m]	15
Shear Coefficient	0.3

SAM Model (Solar)

Input	Value
Rated Power [kW]	[1; 2; 3]
Tilt [degree]	35
Azimuth [degree]	180
Total System Flow Rate [kg/s]	0.0439626
Working Fluid	Water
Diffuse Sky Model	Isotropic
Irradiance Inputs	Beam and Diffuse
Albedo	0.2
Collector Area [m^2]	[1.65; 3.3; 4.95]
FRta	0.73
FRUL [$W/m^2.C$]	4.12
Incidence Angle Modifier	0.91
Test Fluid	Water
Test Flow [kg/s]	0.0439626

HOMER Legacy Model (Wind)

Input	Value
Rated power [kW]	[1; 2; 3]
Turbine Power Curve	✓
Hourly wind speed averages [m/s]	✓
Hub Height [m]	15
Lifetime [year]	20
Altitude Above Sea Level [m]	*
Anemometer Height [m]	10

*location dependent

2.3.9 Hub height and wind shear coefficient sensitivity analysis

The hub height and wind shear coefficient are two key variables in modeling wind turbines. This is due to the effect of the wind shear coefficient on the wind speed at the hub height. As previously mentioned, the wind speed at the hub height is calculated based on the height of the measured wind speed, the desired hub height and the wind shear coefficient. In this case, the modeled hub height chosen was 15m. Furthermore, this value is considered to be measured as the height from the ground up to the turbine hub. The figure below shows how the selected wind shear coefficient of 0.3 affects the wind speed for each wind profile and height above the ground.

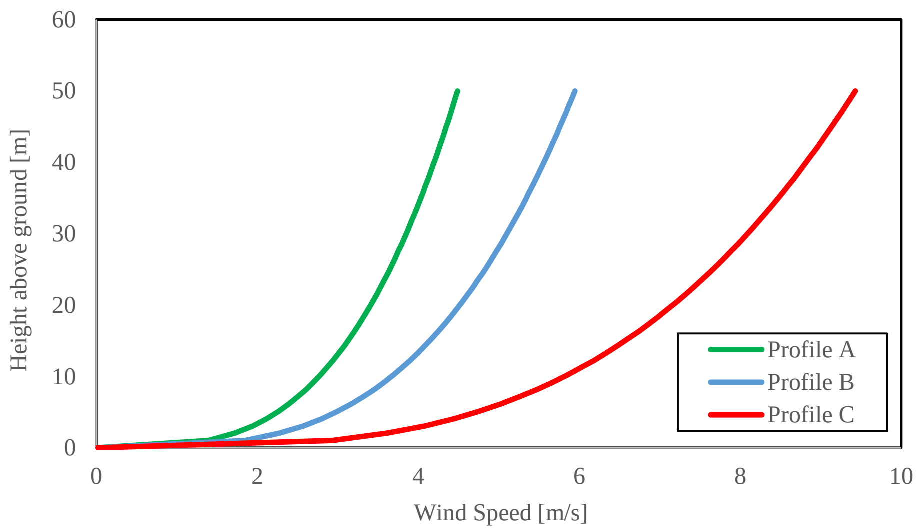

Figure 10 - Effect of the wind shear coefficient (or power law coefficient) on the wind speed at different heights.

By increasing or decreasing the hub height, the wind speed behavior at this scale is significantly different. Therefore, depending on the site of the installation, the output of the wind turbine can have a large variation. Power results for different heights are shown in Subchapter 3.3.1 and are discussed prior to the overall wind turbine results. Finally, the chosen hub height is under the assumption that the wind turbine is in an urban area that has an average height of 15m for the available wind turbine installation sites.

2.3.10 Simulation result post-processing

After the simulations, the data for power generated by the system for each of the 8760 hours of the year was exported to a Matlab script that organized these values in daily sums for each profile, each system (wind turbine and solar collector) and each rated power, for both models. After this, the resulting daily sums were used in an Excel spreadsheet to calculate the operational grid costs and the yearly savings of the systems as well the estimated payback of the initial investment. This was achieved by a cycle that performs a value check for each day. If the total amount of energy generated daily was equal or more than 11 kWh (energy required for each day of the year to heat the hot water, Subchapter 2.3.1) then the grid cost would be 0 €, if that energy total was less than 11 kWh then the cost of the grid purchases for that day would be equal to the average price per kWh, in Portugal (0.162 €), multiplied by the power difference between the energy generated and the power required. After these calculations were made for all profiles, systems and the two models used, the results were plotted and are displayed in Chapter 3, with further analysis in Chapter 4.

The cost of the turbines, collectors and the grid purchases are shown without value-added tax, as depending on the locations and consumer, they can differ in their final price and may not even be a cost. In doing so, without accounting for the tax, these systems can easily be compared at the same financial scale in a simple preliminary analysis. We started by performing a simple payback period calculation, and based on the obtained results, the paybacks for each of the systems had values that intuitively did not merit a more complex financial analysis. The range of the results are such that, by performing more complex calculations, taking into consideration inflation and taxes, the payback periods for the studied profiles would remain largely the same. As seen in the results from the next chapter, the payback for wind turbines for profiles A and B would still be over 20 years. This would also be the case for the payback period for solar thermal collectors, which for profile C, would remain in values of over 10 years. Ultimately, the simple financial analysis yields the same range of results and conclusions as a more complex analysis.

Chapter 3 - Simulation Results

3.1 Chapter summary

In this chapter, the most relevant of the extensive results from the simulations carried out in the SAM and HOMER models, as well as the subsequently Excel and Matlab calculations, are shown, for the energy distribution, power generation, financial evolution and costs of the system.

3.2 Available resource behavior

The three annual wind profiles are displayed, in daily averages, in figures 11, 12 and 13. For profile A, the wind throughout the year is consistent with a slight increase in the winter and decrease in the summer. Profile B is also quite consistent throughout the year, yet unlike profile A, there is an increase in wind speeds in the winter as well as in the summer. Making profile B an interesting case study for a wind turbine application. Finally, the wind data shows that profile C presents the highest wind speed profile, as well as the most common wind profile, lower wind speeds in the summer and higher wind speeds in the winter.

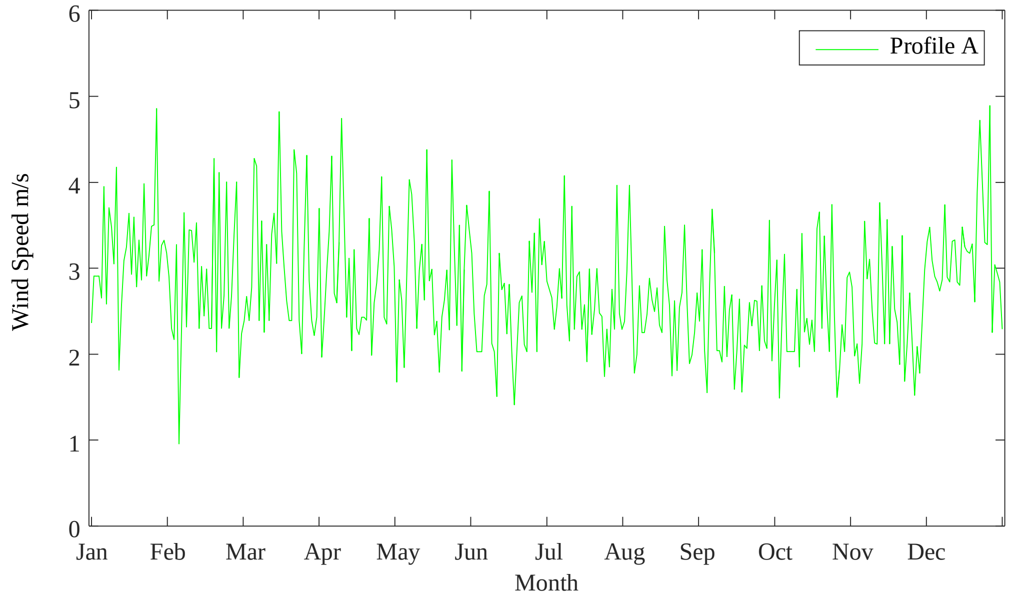

Figure 11 - Annual daily average wind speed for profile A.

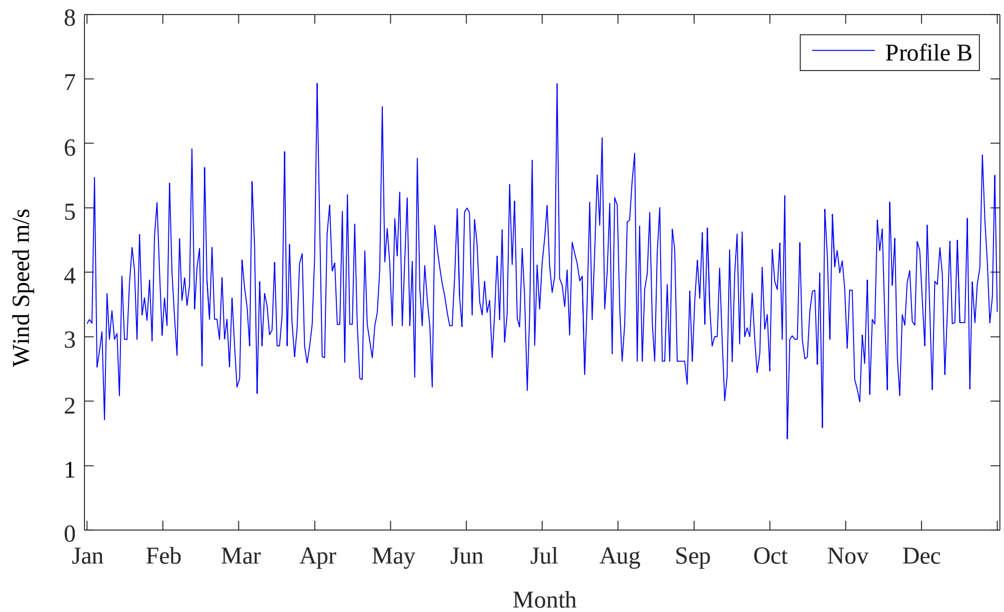

Figure 12 - Annual daily average wind speed for profile B.

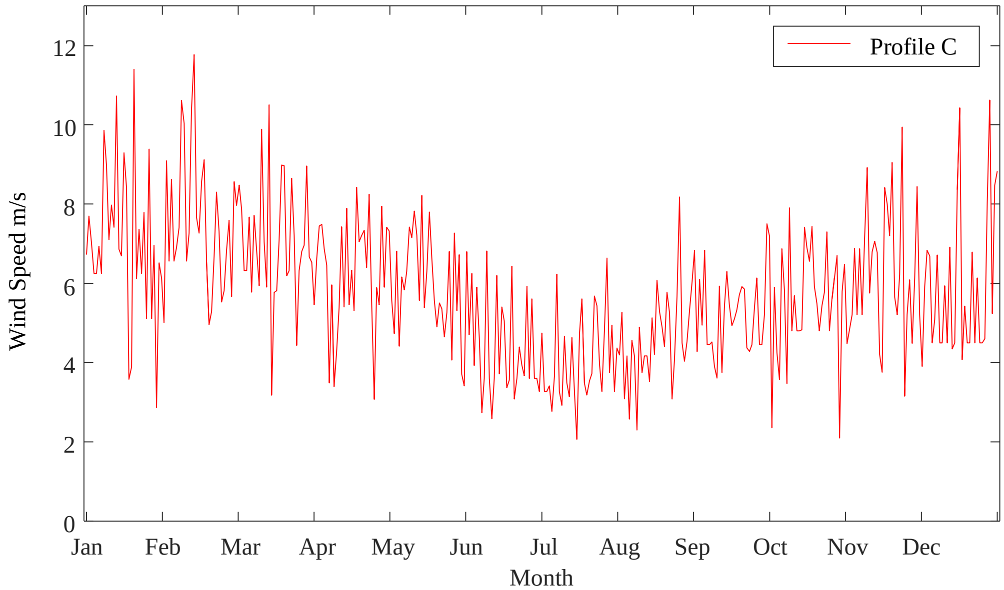

Figure 13 - Annual daily average wind speed for profile C.

Regarding solar radiation profiles, Figure 14 through Figure 16 show the daily averages of the solar incident radiation. The data suggests there is a higher amount of available solar radiation during the summer than during the winter. As mentioned in Chapter 2, data for profiles A and B are similar, while profile C has overall lower values. Nonetheless, the incident radiation evolves in a similar way throughout the year for each of the profiles.

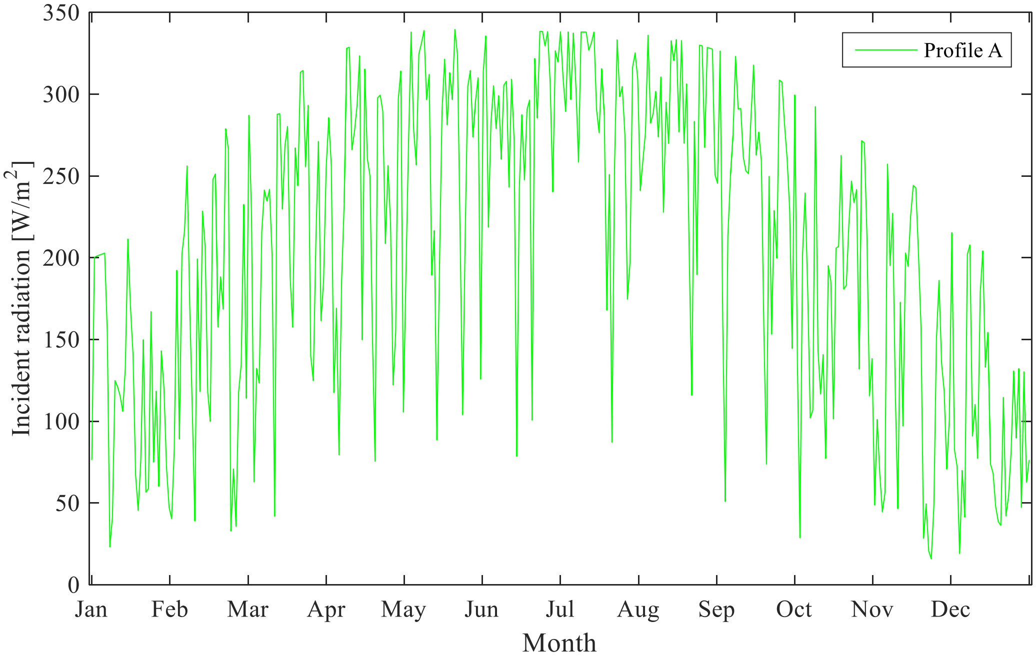

Figure 14 - Annual daily average incident radiation for profile A.

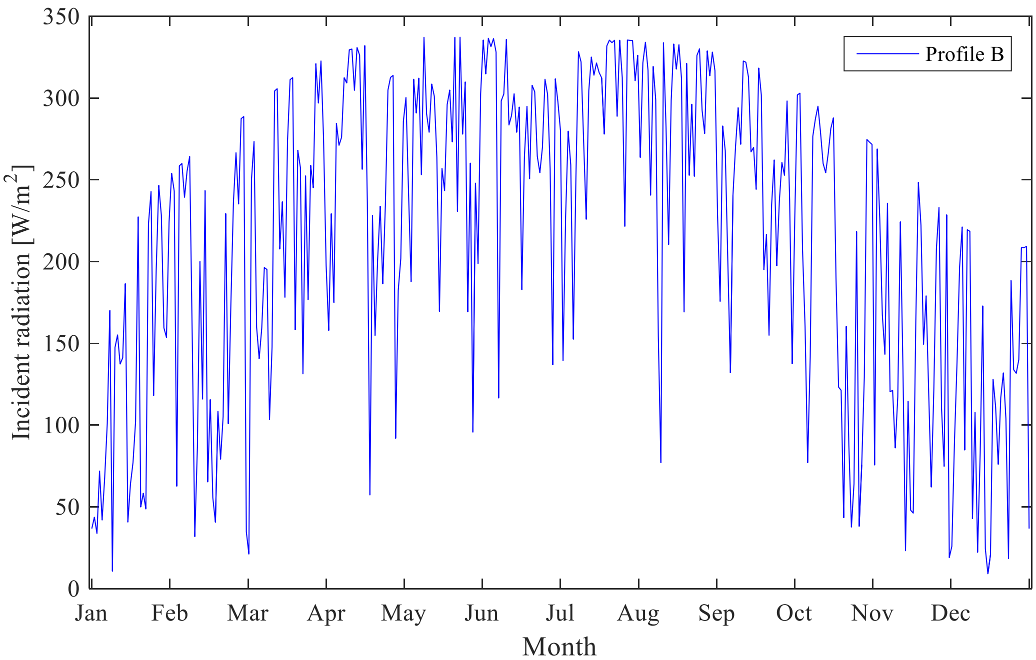

Figure 15 - Annual daily average incident radiation for profile B.

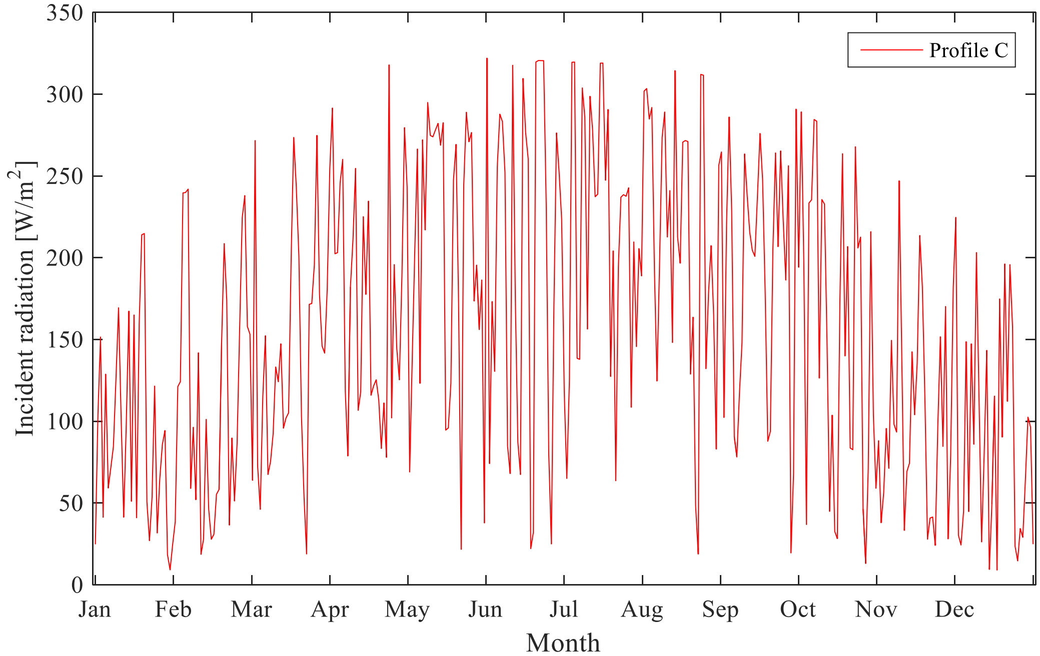

Figure 16 - Annual daily average incident radiation for profile C.

The disparity from day to day in both the solar and wind data is mainly influenced by the meteorological behavior of each location. However, the data still allows for a good understanding of the resource behavior.

3.3 Power results

3.3.1 Wind turbine output

As mentioned in the previous chapter, the hub height can significantly affect the power output of a turbine due to its effect on the wind speed. This effect is shown in table 4, for a 1kW turbine (results obtained by modeling different heights in SAM).

Table 4 - 1kW wind turbine power output at different hub heights for all profiles.

	[kWh/year]		
Hub height [m]	Profile A	Profile B	Profile C
15	250	369	2033
20	352	510	2597
30	572	808	3496

As the results show, variations in the hub height will affect the annual power output. Therefore, when studying a possible application for wind turbines, it is recommended that the installation site be modeled and reviewed before starting the project.

Now, for the simulation results, the following table shows the annual energy generated by the wind turbines.

Table 5 - Annual energy generated by the wind turbines, for all study profiles.

	Energy generated (Wind) [kWh/year]		
Installed Capacity	1 kW	2 kW	3 kW
Profile A (SAM)	140.58	250.25	395.55
Profile A (HOMER)	140.78	251.64	396.12
Profile B (SAM)	369.37	715.41	1085.82
Profile B (HOMER)	371.12	718.32	1089.26
Profile C (SAM)	2033.10	4061.36	6102.13
Profile C (HOMER)	1995.42	3985.70	5988.74

Figure 17 shows the total monthly energy production for the study profiles. A quick analysis of the graph indicates that profile C has a high wind potential, while profiles A and B yield less than favorable results. Since the ratio of energy generated to rated power is similar for every system, the figures all have a comparable presentation, therefore only the 1kW variation will be shown and the rest can be viewed in appendix 2.

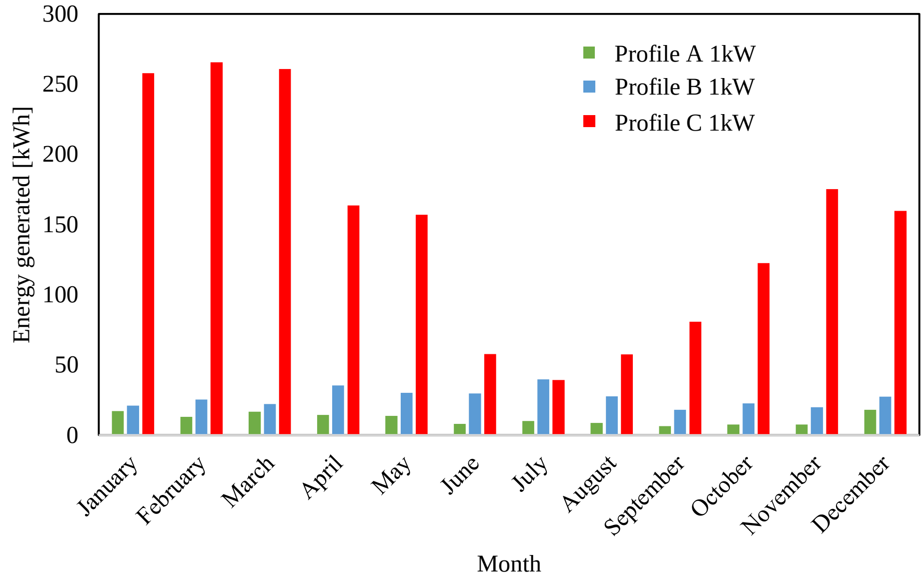

Figure 17 - Total energy generated, by a 1kW wind turbine for each profile and every month of the year (results from SAM simulations).

The output file for HOMER is in hourly data, therefore, in order to calculate the monthly sums in HOMER the hourly data was exported to Matlab. The results from the HOMER model are almost identical to the SAM model. However, it is important to note that there is a slight difference between the results from HOMER and SAM. Despite this, the differences are irrelevant since both models use the same method of calculating the power output of the turbines. Furthermore, since this does not significantly affect the overall values then only the 1kW turbine data was shown for HOMER as not to repeat what the SAM figures already presented, and as mentioned above, the rest can be seen in appendix 2.

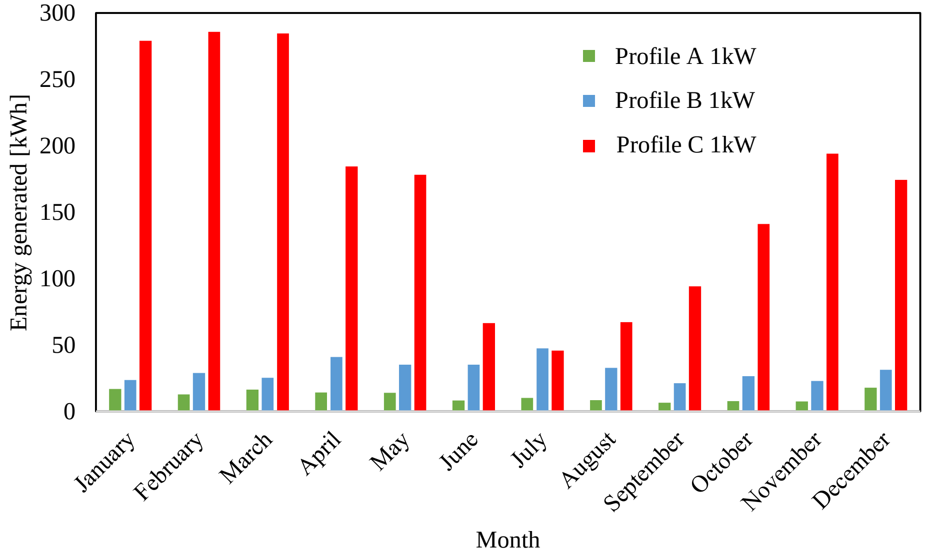

Figure 18 - Total energy generated, by a 1kW wind turbine for each profile and every month of the year (results from HOMER Energy simulations).

3.3.2 Solar collector output

The table below presents the annual energy generated by the solar thermal collectors. The profile of the power output for all the solar collectors in generally the same, therefore the power output for the rest of the systems not shown can be seen in appendix 2 and the table below shows the values for each profile.

Table 6 - Annual energy generated by the solar thermal collectors, for all studied profiles.

	Energy generated (Solar) [kWh/year]		
Installed Capacity	1 kW	2 kW	3 kW
Profile A	935.88	1655.59	2107.56
Profile B	959.36	1714.76	2161.67
Profile C	600.85	1096.98	1461.92

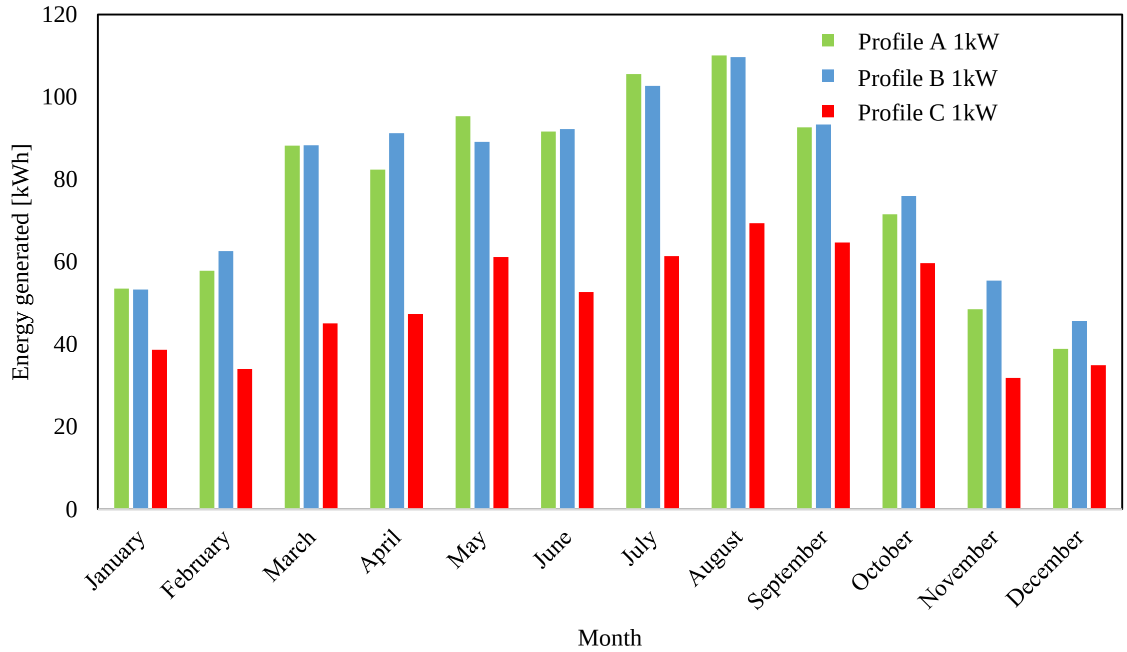

Figure 19 - Total energy generated, from a 1kW solar thermal collector for each profile, for every month of the year (results from SAM simulations).

3.4 Financial results

3.4.1 Operational and maintenance costs

As previously mentioned in Chapter 2, the maintenance costs are always a fixed amount for both technologies. For wind turbines below the rated power of 10kW, the maintenance costs stand at an average of 35€$\cdot$year^{-1}. Meanwhile, for the solar thermal collectors this value is 1% of the initial investment cost of the entire system. The only costs that vary are the operational costs, which represent the grid purchases that occur each day that the renewable energy production does not meet the demand. Furthermore, as a baseline comparison, we have calculated the cost of the grid purchases, without any renewable or external power source, as 649.56 €$\cdot$year^{-1} for the household in this case study. The operational costs for each of the wind power variations is presented below.

Table 7 - Annual grid purchases using a wind turbine, for each profile and each rated system power.

	Grid Purchases (Wind) [€/year]		
Installed Capacity	1 kW	2 kW	3 kW
Profile A (SAM)	626.82	615.51	585.57
Profile A (HOMER)	626.79	608.85	585.48
Profile B (SAM)	598.04	536.02	482.78
Profile B (HOMER)	589.52	535.63	482.39
Profile C (SAM)	390.86	240.94	185.05
Profile C (HOMER)	365.33	242.94	186.33

The fixed maintenance cost for the solar thermal collectors for the 1kW, 2kW and 3kW system are 12€, 20€ and 28€, respectively.

Table 8 - Annual grid purchases using a solar thermal collector, for every profile and each rated system power.

	Grid Purchases (Solar) [€/year]		
Installed Capacity	1 kW	2 kW	3 kW
Profile A	424.21	381.72	308.59
Profile B	494.35	372.14	299.84
Profile C	552.35	472.09	413.05

3.4.2 Levelized cost of energy

Based on the annual costs for each system, the levelized cost of energy (LCOE) can be calculated. This is accomplished by using Eq.(6), which results in the $€\cdot kWh^{-1}$ of each system and are presented in the next tables.

$$\mathrm{LCOE} = \frac{C_R}{E_u} \tag{6}$$

Where LCOE is the levelized cost of energy in €·kWh^{-1}, C_R is the cost of the renewable system each year in € (calculated using Eq. (7)), and E_u is the useful energy generated by the system in kWh.

$$C_R = OC + MC + \frac{C_S}{L_S} \tag{7}$$

Where MC is the maintenance cost of the system in € and $C_S \cdot L_S^{-1}$ is the initial investment of the renewable system divided by the lifetime of the project.

Table 9 - Wind turbine LCOE.

	Renewable energy cost (Wind) [€/kWh]		
Installed Capacity	1 kW	2 kW	3 kW
Profile A (SAM)	5.19	3.04	1.99
Profile A (HOMER)	5.18	3.03	1.99
Profile B (SAM)	1.87	0.98	0.66
Profile B (HOMER)	1.86	0.98	0.66
Profile C (SAM)	0.26	0.16	0.13
Profile C (HOMER)	0.27	0.16	0.14

Table 10 - Solar thermal collectors LCOE.

	Renewable energy cost (Solar) [€/kWh]		
Installed Capacity	1 kW	2 kW	3 kW
Profile A	0.36	0.30	0.21
Profile B	0.59	0.29	0.20
Profile C	1.04	0.54	0.37

3.4.3 Wind turbine payback projection

The figures in this section show the cumulative cash flows for a small wind application, a null cumulative cash flow corresponds to the simple payback time. Both SAM and HOMER projections, for 10 years, are shown for profile C. For profiles A and B the payback periods were not acceptable and are addressed in the next chapter (nonetheless, they are presented in appendix 3).

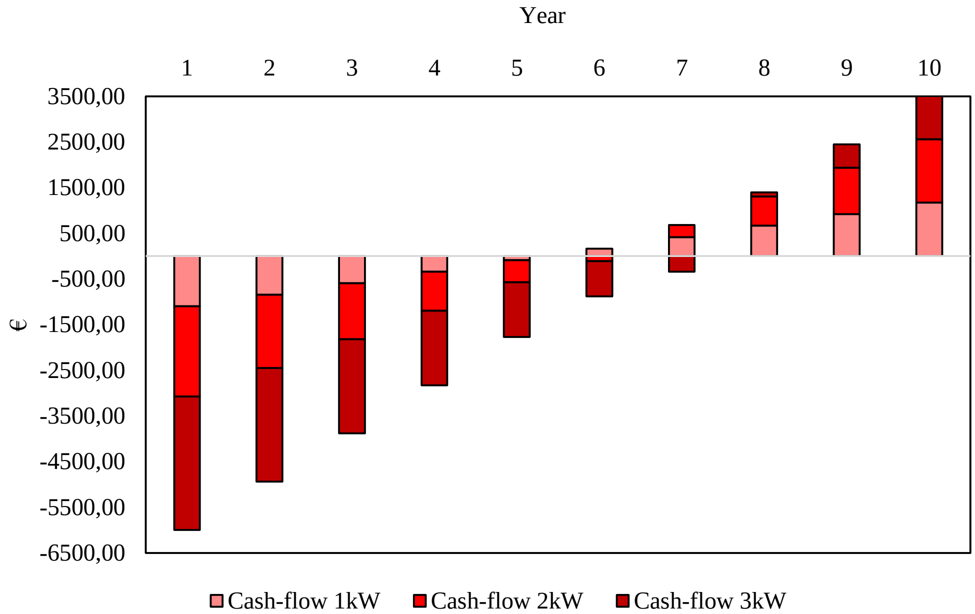

Figure 20 - Payback projection for all the wind turbines for profile C, based the SAM model results.

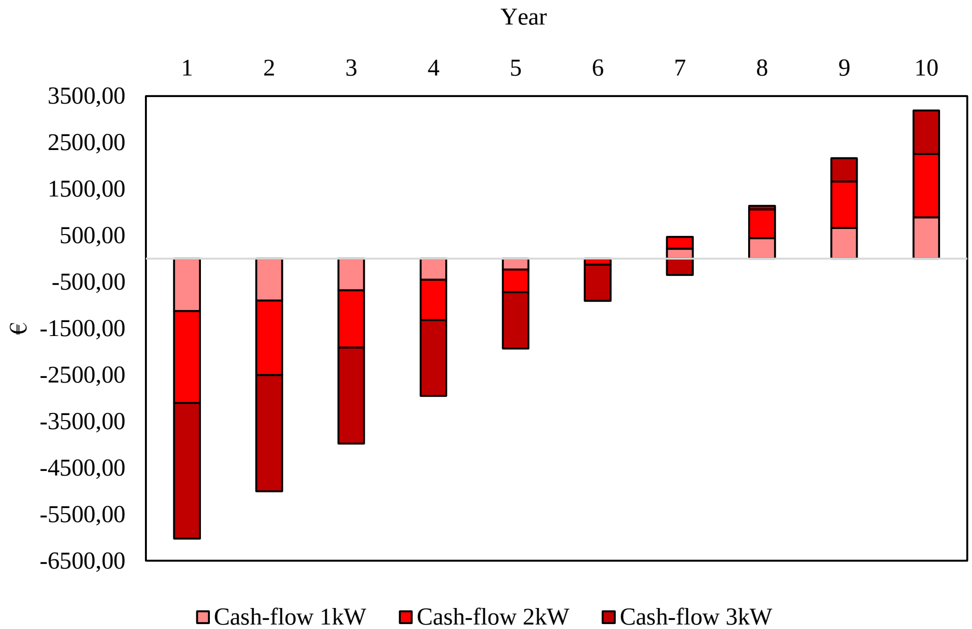

Figure 21 - Payback projections for all the wind turbines for profile C, based on the HOMER model results.

3.4.4 Solar collector payback projection

The following figures are the cumulative cash flows for the solar thermal collectors modeled in SAM, as with the wind turbines, a time period of 10 years is shown.

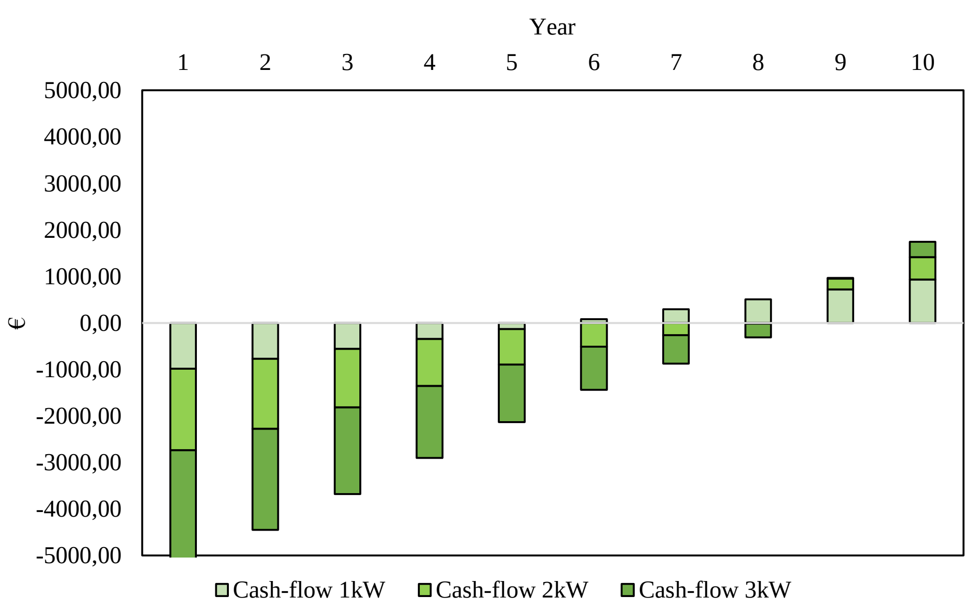

Figure 22 - Payback projection for all the solar thermal collectors for profile A, based on the SAM model results.

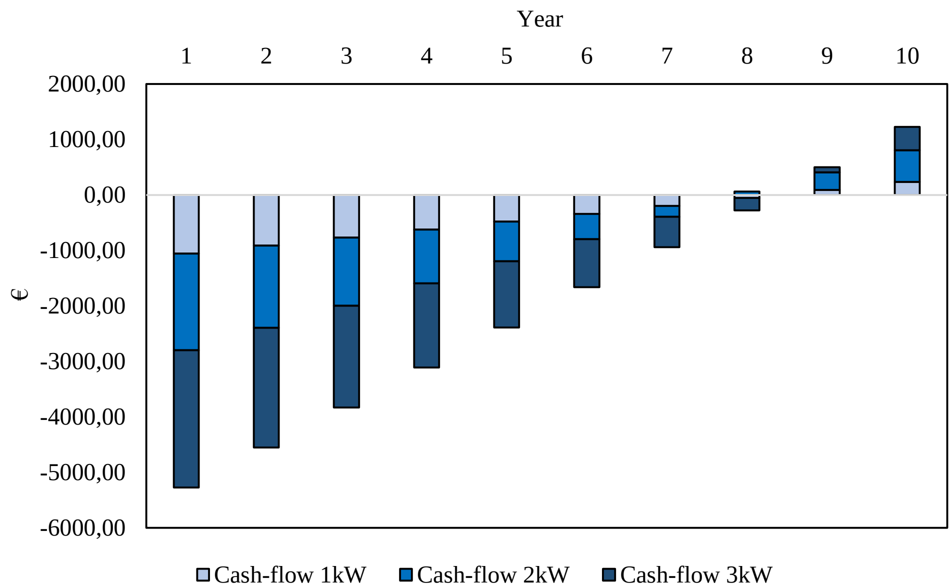

Figure 23 - Payback projection for all the solar thermal collectors for profile B, based on the SAM model results.

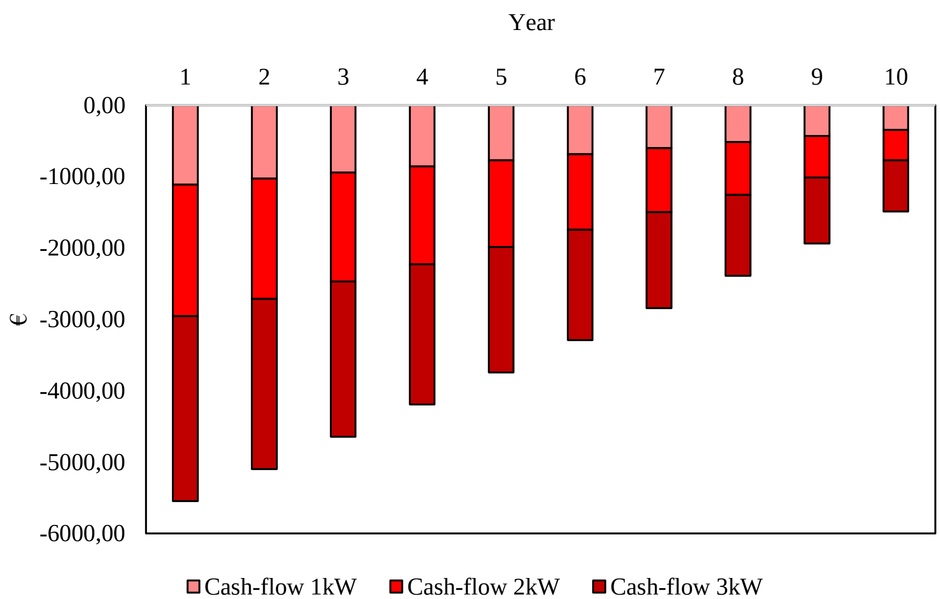

Figure 24 - Payback projection for all the solar thermal collectors for profile C, based on the SAM model results.

Chapter 4 - Results Discussion & Future Developments

4.1 Chapter summary

This chapter is dedicated to discussing the main findings from the results in Chapter 3, as well as possible system combinations and some future opportunities for wind power.

4.2 Power results discussion

4.2.1 Wind (Power)

The analysis of the wind turbine outputs will be divided into three sections, one for each case study. First, profile A presents low-range wind speeds. Here, the wind is very stable and, while the values are low for a wind turbine application, the overall profile of the wind has no significant variations throughout the year. This behavior allows the system to generate energy at a steady rate. However, since the wind speeds are so low, the power that can be extracted from the wind, considering the available technology, is also low. With yearly power outputs of 140 to 400 kWh this represents at most 10% of the necessary energy demand for heating. With this in mind, from the perspective of generated power, these values are too low for any of the considered wind turbines to be a viable option.

Second, profile B presents mid-range wind speeds. Generally speaking, mid-range wind speeds do not translate to mid-range power outputs, this is determined by the efficiency and power-curve of the wind turbine used. For example, with a higher efficiency and lower cut-in speed a turbine could have the potential to generate more power. As previously mentioned the wind speeds increase during the summer which provided an interesting wind profile. The summer increase allows for energy production during this season at the same scale as during the winter. Although the wind speeds have a higher variation than profile A, the overall energy production is also fairly linear during the entire year. The total energy production is 300 to 1000 kWh per year, which can account for 25% of the energy required for the water heating process.

The final case study is profile C. It was chosen due to being one of the regions in Portugal with the highest urban wind potential and this is reflected in the power output simulations. Of the three case studies, it has the highest yearly energy production. However, the wind speeds have a large variation from season to season. The speeds in the winter are 2 to 3 times higher than in the summer. This effect can also be seen in the power output of the turbines. During the winter there is a high amount of energy production and during the summer it falls to values equal to profiles A and B. This results in a total yearly energy production of 1800 to 6100 kWh each year, however, this energy is poorly distributed. The significance of this is that the energy generated in the season with higher wind speeds is being wasted. Daily values for energy production, in these higher speeds, can be up to 7 times higher than required by the hot water demand. Ultimately, this means that even if the total energy generated each year, by the highest power rated system, exceeds the energy demand by 50%, the useful energy is much lower. Despite this, the renewable fraction ranges from 40 to 70%, which are values that allow for a cost-effective deployment.

4.2.2 Solar (Power)

For every profile, the behavior of the solar resources is similar, distinguished only by the scale of energy production. When comparing the rated system powers, the best case scenario is profile A with a total yearly output ranging from 900 to 2100 kWh. The renewable fraction with a 1kW system is only 25%, nevertheless, with a higher power system the renewable fraction can reach 50% of the total energy required. Profile B is equivalent to what is seen in profile A, with slight differences in the power output.

Profile C is the case study with the worst solar results. With a power output of 600 to 1400 kWh and at most a 35% renewable fraction. For locations with this profile, in terms of power output, solar thermal collectors prove to not be best option.

Generally speaking, unlike the wind turbines, the energy generated by the solar systems is constant. This allows the system to always contribute some energy for the daily demand and to always have a presence when installed as part of a hybrid system. Furthermore, the system may still retain some thermal energy in the early night hours due to the fluid flowing in the tubes. This happens if there was a high amount of solar radiation during the day and the system has not had time to cooldown, or if water in the system is still hot and the water tank is also hot, in this case the solar panel fluid has no means of transferring the heat to another system. Finally, there is no single day that the energy generated surpasses the demand which means all the production can be considered useful.

4.3 Financial results discussion

As seen in the levelized cost of energy calculations, the cost of the renewable energy is high when compared to other conventional power sources for water heating. This is the reason why renewable energy is subsidized, which in part is helping market implementation and development of the technology. Nonetheless, values for the wind turbines in Profile C show favorable results for this renewable option.

4.3.1 Wind (Financial)

A view of the O&M costs for the wind turbines shows that the operational costs for profiles A and B are very high. This causes an interesting effect, yet unfavorable, on the payback for profile A, the grid purchases (operational costs) and maintenance costs for each year, of a 1kW or 2kW wind turbine, are actually higher than the grid purchases with no renewable system in place. This means that a payback for these turbines is not possible, which leads to locations with this profile not being recommended for a wind application. The only option where there is a calculated payback is with the 3kW system, however, the payback is this case is 114 years, which is unacceptable. For profile B this long payback period occurs with every rated power, although not as extreme as profile A, the best case scenario is a payback of 24 years for a 3kW turbine. Profile C is the only one with positive results for the financial aspect of this system. Here the payback period ranges from 5 to 7 years, depending on the installed power.

4.3.2 Solar (Financial)

The overall lower costs of solar technology are an advantage to the implementation of these types of systems. A payback is possible for profiles A and B, while profile C has less promising results. With a minimum payback period of 12 years, it is not recommended for solar technology as a primary source of renewable energy. Profiles A and B present a better scenario, with a payback from 5 to 8 years. Comparing the systems, the best case scenario is for profile A, with a 1kW solar thermal collector. The payback period is 5 years, however, the renewable fraction is only 25%. With a higher investment the solar fraction can reach 50% of the total energy required, although this would impact the payback, increasing it to 8 years, which can still be a viable option. For profile B the lowest payback is not for the lowest cost system but for the 2kW collector, with a payback of 7 years and reaching a renewable fraction of approximately 40%. Considering all the options, the best would be profile A. Here, all the systems have a low payback period and the renewable fraction can reach satisfactory levels.

4.4 Energy storage

When there is excess energy, to mitigate its loss, there can be a storage system in place such as a secondary water tank to harness the overflow, as mentioned in Chapter 2. Therefore, a system of auxiliary tanks was modeled in Matlab to test whether this excess energy can be efficiently stored and used at a later time. When the main water tank is at full capacity, the excess energy is delivered to the secondary tank, and so on. The Matlab routine simulates the heat transfer to and from the water tanks, each day, while accounting for a daily heat loss of the tanks. Figure 25 shows a simplified diagram of how the code handles these calculations.

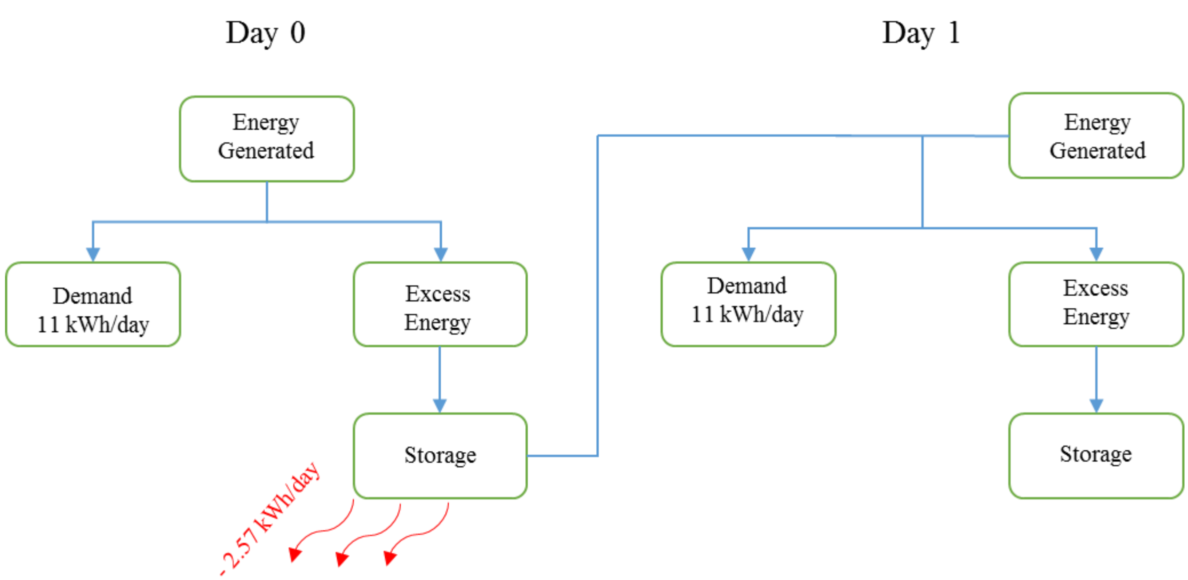

Figure 25 - Simplified Matlab storage calculations routine.

The daily heat loss used in this simulation is the upper limit allowed by the regulation for housing energy efficiency [32]. As for the chosen location to perform this study, the only viable option with a large amount of excess energy is locations with the behavior of profile C. The routine allows for the simulation of any number of water tanks and any capacity. The secondary tanks were modeled has having a capacity of 200 L, which represent the total amount of water used each day.

The results of the routine show that, at most, 10% of the excess energy, approximately 200 kWh, is stored and used when there is one 200 L tank installed. This translates to a 30 to 40€ saving each year, which is insufficient to justify the purchase of an additional tank. Multiple tanks were also modeled, with similar unfavorable results. Having multiple water tanks will increase the amount of energy stored, approximately 10% per tank, but will significantly increase the investment to implement this system. In sum, having storage options would allow for some of the wasted energy to be recovered, but ultimately is not cost-effective.

4.5 Possible system and resource combination

To determine if any of the studied profiles present a complementary wind and solar resource availability, a correlation analysis was done. To achieve this, the data for the energy potential of both resources were plotted in relation to each other. Analyzing all the data (figures 26 through 28), the wind and the solar power complement each other for wind profile C, where a more linear evolution between wind and solar power can be found. This relationship exists due to a lack of wind during the summer, therefore having a solar panel in that season could potentially be beneficial to the renewable application and help mitigate the intermittency of the resources. With this in mind, and because profile C is the only one with a favorable wind turbine payback, it would be worth studying the application of a hybrid system. Furthermore, taking into consideration that each profile has an equivalent solar evolution throughout the year, this analysis will focus on wind profile C combined with solar profile B. In doing this, the most favorable profile for wind power can be coupled with the best solar power profile.

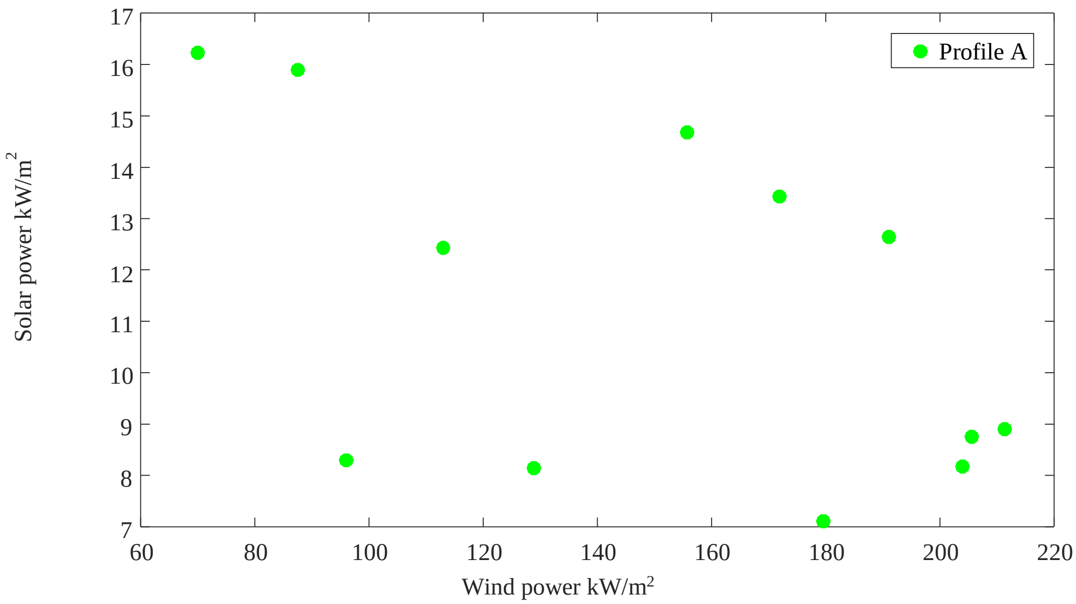

Figure 26 - Correlation between solar power and wind power for profile A.

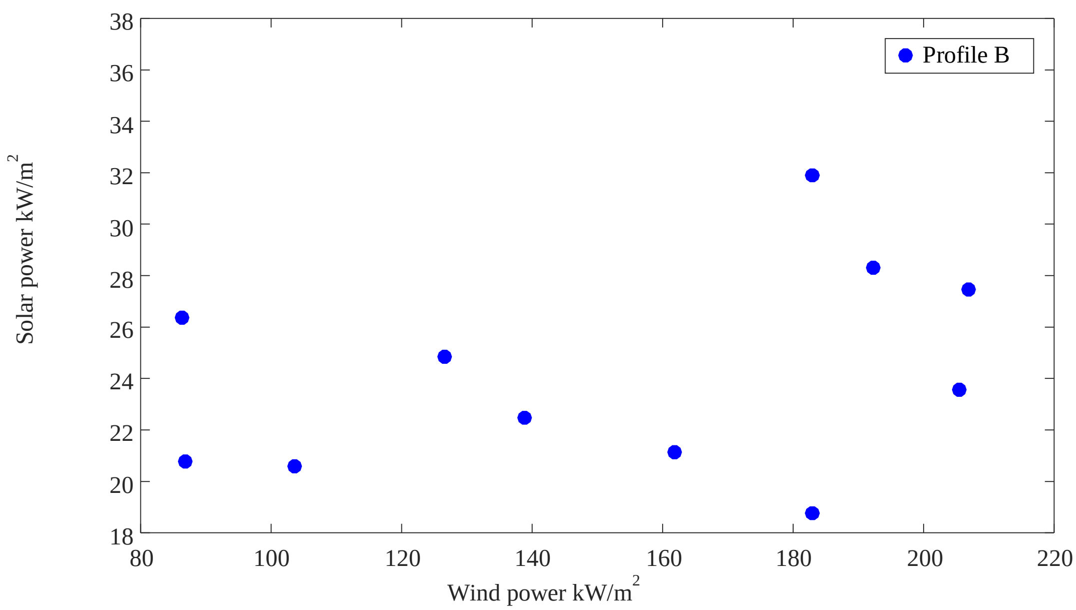

Figure 27 - Correlation between solar power and wind power for profile B.

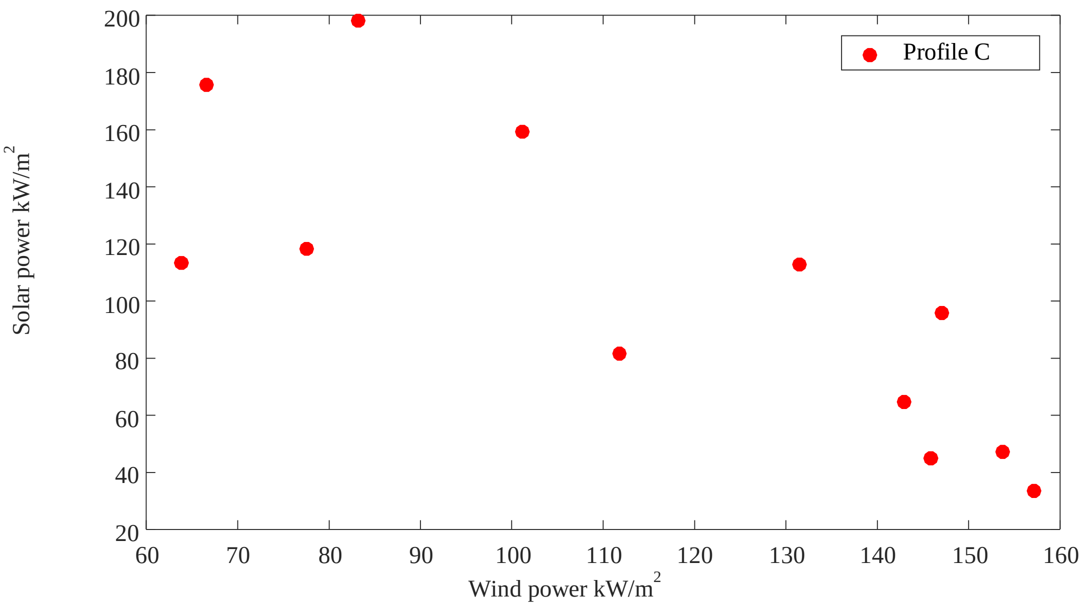

Figure 28 - Correlation between solar power and wind power for profile C.

The results indicate that the best hybrid system would be a 1kW wind turbine with a 2kW solar collector. While this system presents a payback equal to a combination of a 1kW turbine and 1kW collector, which is 6 years, the renewable fraction is 75%, which is higher and results in added yearly savings.

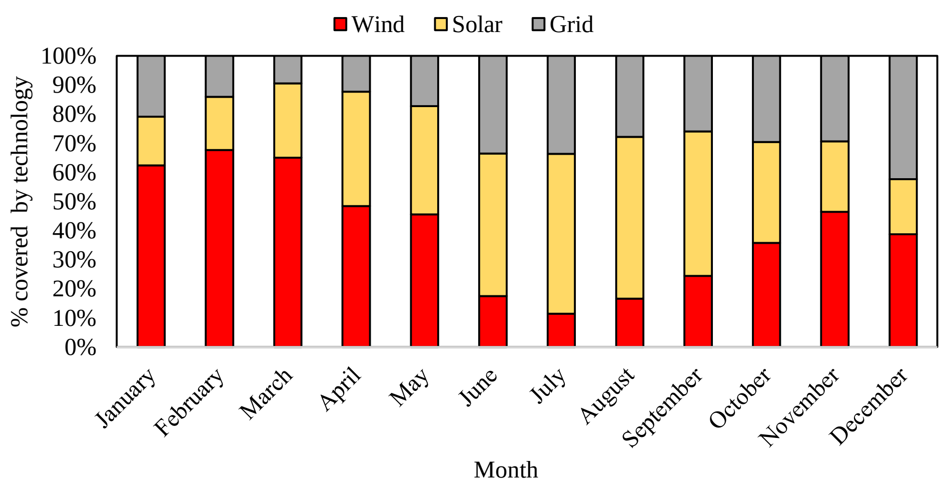

Figure 29 - Power generated by a hybrid 1kW wind turbine, 2kW solar thermal collector, and energy grid, relative to the energy demand.

4.6 Future goals for wind power

4.6.1 Maximum wind potential methodology

To understand how wind turbines must evolve we must first study the resource limitations that exist for each wind profile. The maximum wind potential can be calculated using the equation below. This equation yields the total amount of power that can be harnessed from the wind per swept area of the wind turbine blades.

$$\frac{P}{A} = \frac{1}{2} \times \rho air \times v^3 \times \frac{16}{27} \tag{8}$$

Where P is the power in the wind in W, A is the swept are of the wind turbine blades in m^2, ρ_{air} is the density of the air in $kg.m^{-3}$, v is the wind speed in $m.s^{-1}$ and 16/27 is the Betz coefficient.

The density of the air was calculated based on the air pressure and the ambient temperature, and the wind speed at hub height is calculated in relation to the wind speed at the measured height and the shear coefficient, as follows:

$$\text{ρair} = \frac{p}{R \times T} \tag{9}$$

Where p is the atmospheric pressure in Pa, R is the specific gas constant for dry air in $J.Kg^{-1}.K^{-1}$ and T represents the air temperature in K.

$$\text{v15} = \text{v10} \times \left(\frac{15}{10}\right)^{sc} \tag{10}$$

Where, v_{15} is the wind speed at a height of 15 meters in $m.s^{-1}$, v_{10} is the wind speed at a height of 10 meters in $m.s^{-1}$ and sc is the shear coefficient.

Finally, the maximum potential equation has a theoretical limit, the Betz coefficient. It represents the upper efficiency limit that any wind turbine could possibly have. If a wind turbine was truly 100% efficient it would remove all the energy from the wind and create a choke point. After passing through the turbine blades, the wind would completely stop, this would create a barrier of sorts, interrupting the flow of the wind. Normally one would multiply the Betz coefficient by the wind turbines efficiency, this efficiency is always lower than 100%. However, in this case the calculations were made assuming a wind turbine with 100% efficiency, a cut-in speed of 0 m/s and no cut-off speed. These conditions will allow a simulation of the maximum power in the wind.

4.6.2 Maximum wind potential results and discussion

Applying the above method, the maximum power in the wind was calculated for every wind profile. The table below shows the annual totals of the wind power potential and the simulated power output of current technology.

Table 11 - Annual wind power potential and average annual wind power simulated.

Power potential [kWh/m^2]		
Profile A	Profile B	Profile C
134.61	302.85	1244.44

Simulated Current Technology [kWh/m^2]		
Profile A	Profile B	Profile C
35.05	96.44	541.00

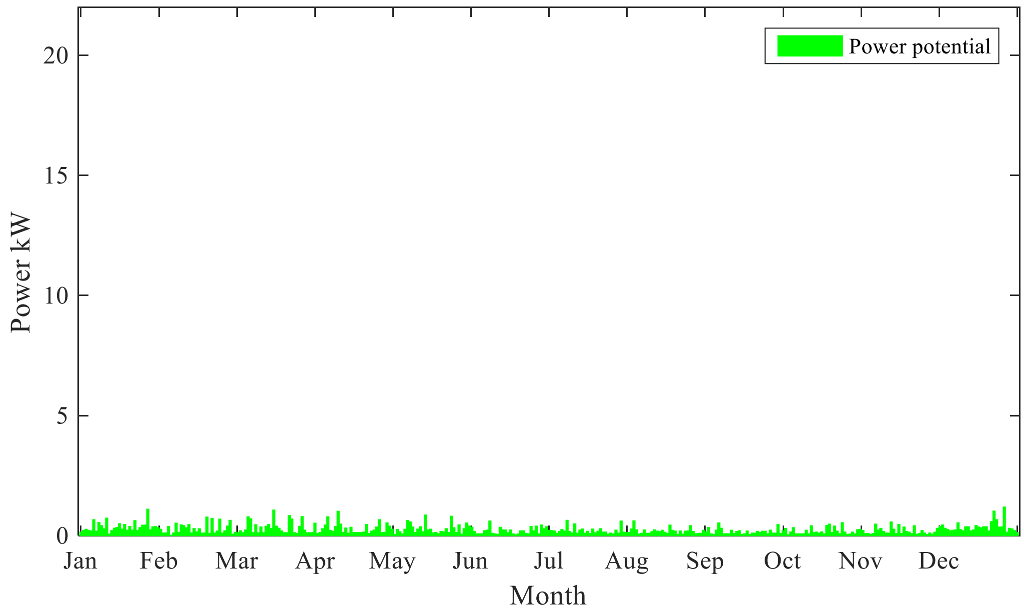

Figure 30 - Daily sum of wind power potential and wind power generated by the simulated system, for profile A.

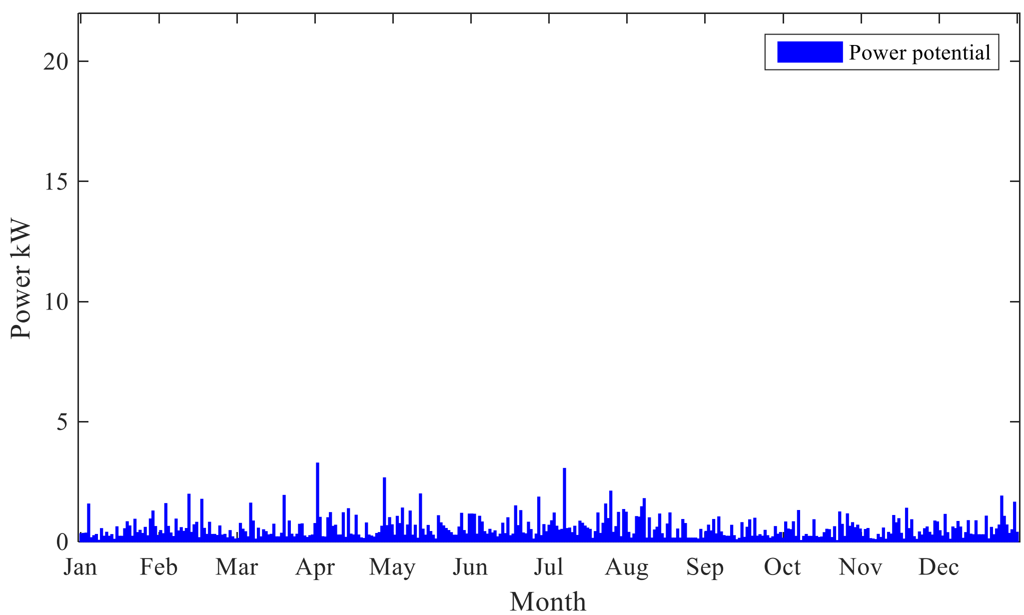

Figure 31 - Daily sum of wind power potential and wind power generated by the simulated system, for profile B.

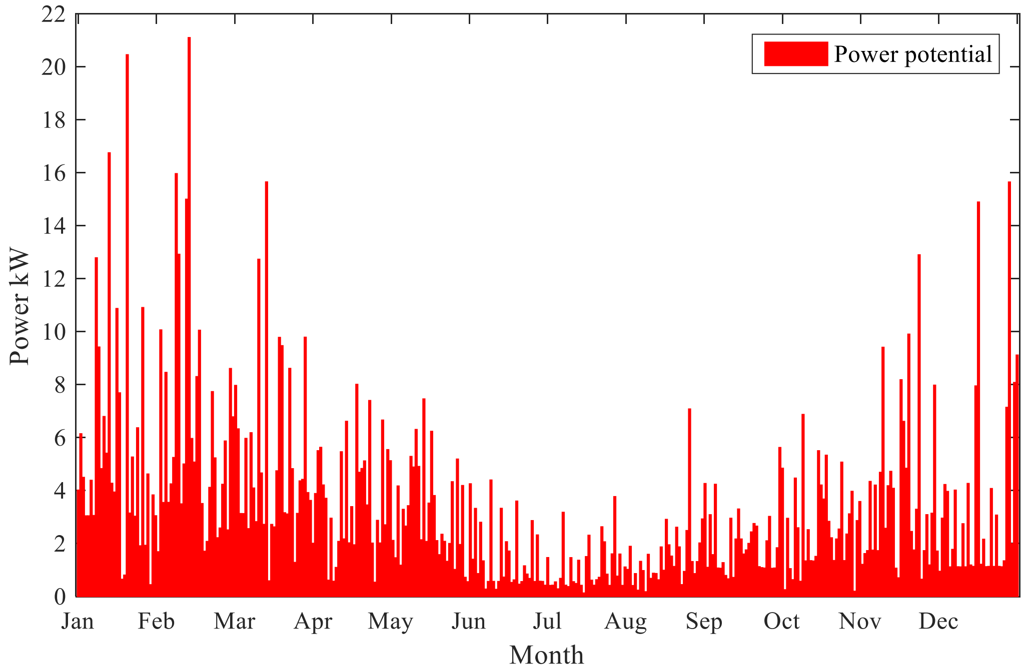

Figure 32 - Daily sum of wind power potential and wind power generated by the simulated system, for profile C.

As evidenced by the above plotted results of the calculations, the wind power potential for profiles A and B fall extremely short of that of profile C. At first, profile B might be discarded as a possible site for wind power applications. However, with some technological improvements, it could still be viable.

4.6.3 Technological and economic goals

This subchapter of the dissertation is dedicated to studying the technological and economical goals for wind turbines. First, the main characteristic that a wind turbine must improve to use the available resource in a more efficient manner is discussed. Second, the optimal cost of the wind turbine is determined.

From a technology standpoint, energy generation from small wind is interesting but not optimal. Some advances must be made to the wind turbines to achieve a decent standing in the market. This is true for both horizontal and vertical axis types. For a quick reference point, the general route when designing a wind turbine is presented in the next figure.

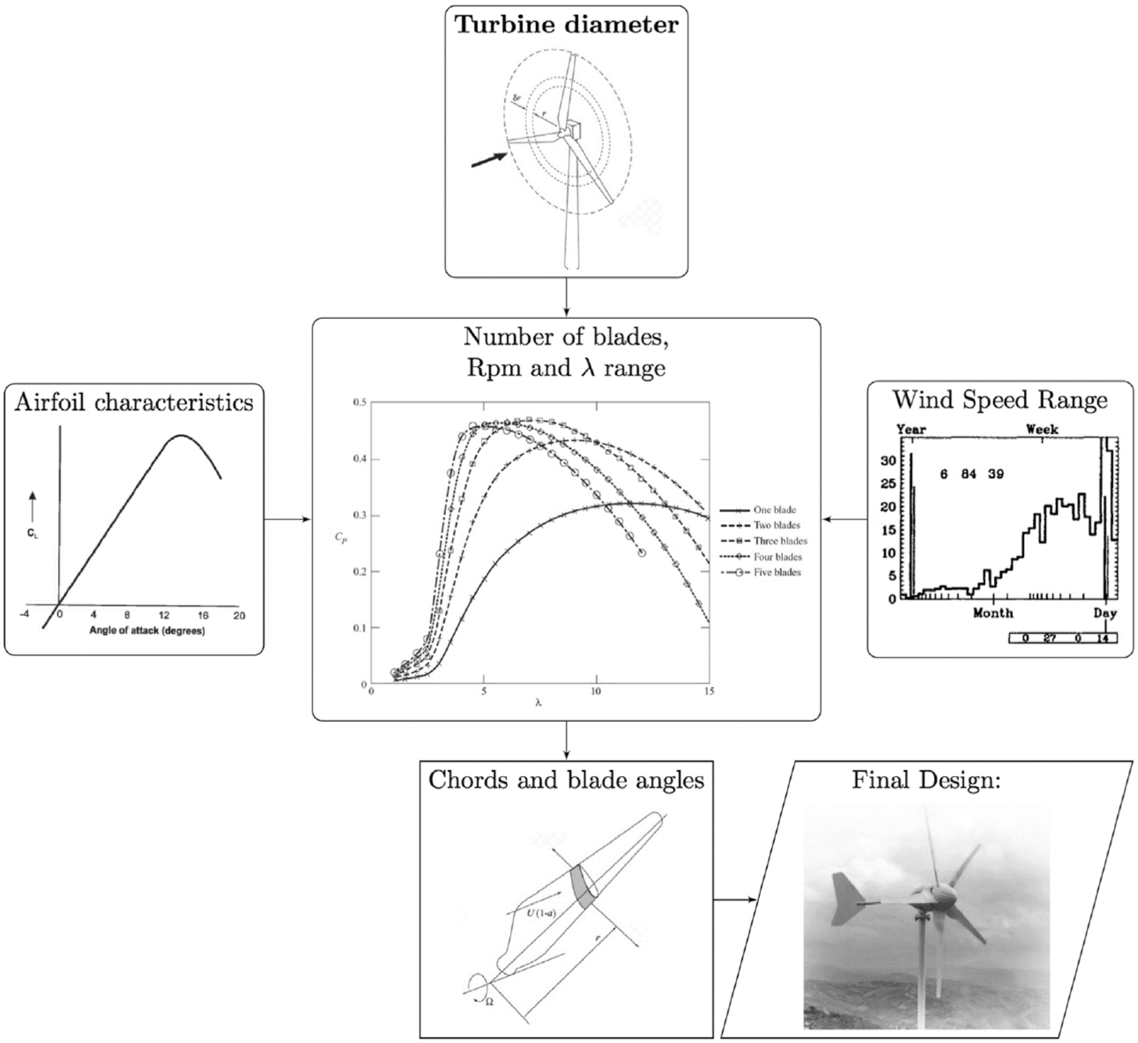

Figure 33 - Design process of a wind turbine [41].

The most studied path to improving the performance of these turbines is through their blades. With large wind turbines, there are pitch controllers to help the blades adjust to the correct angle to better harness the power of the wind. However, this solution is not viable for a small turbine due to the costs of pitch control at this scale. Therefore, the most common answer resides in increasing the performance of the blades and their behavior, or harnessing the wind in innovative ways (as mentioned in Subchapter 1.3.3). This can result in lower cut-in speeds and rated speeds, which are the wind speed at which the turbines start generating power and reach their rated power output, respectively (for further reading about improving wind turbines[39]–[41]

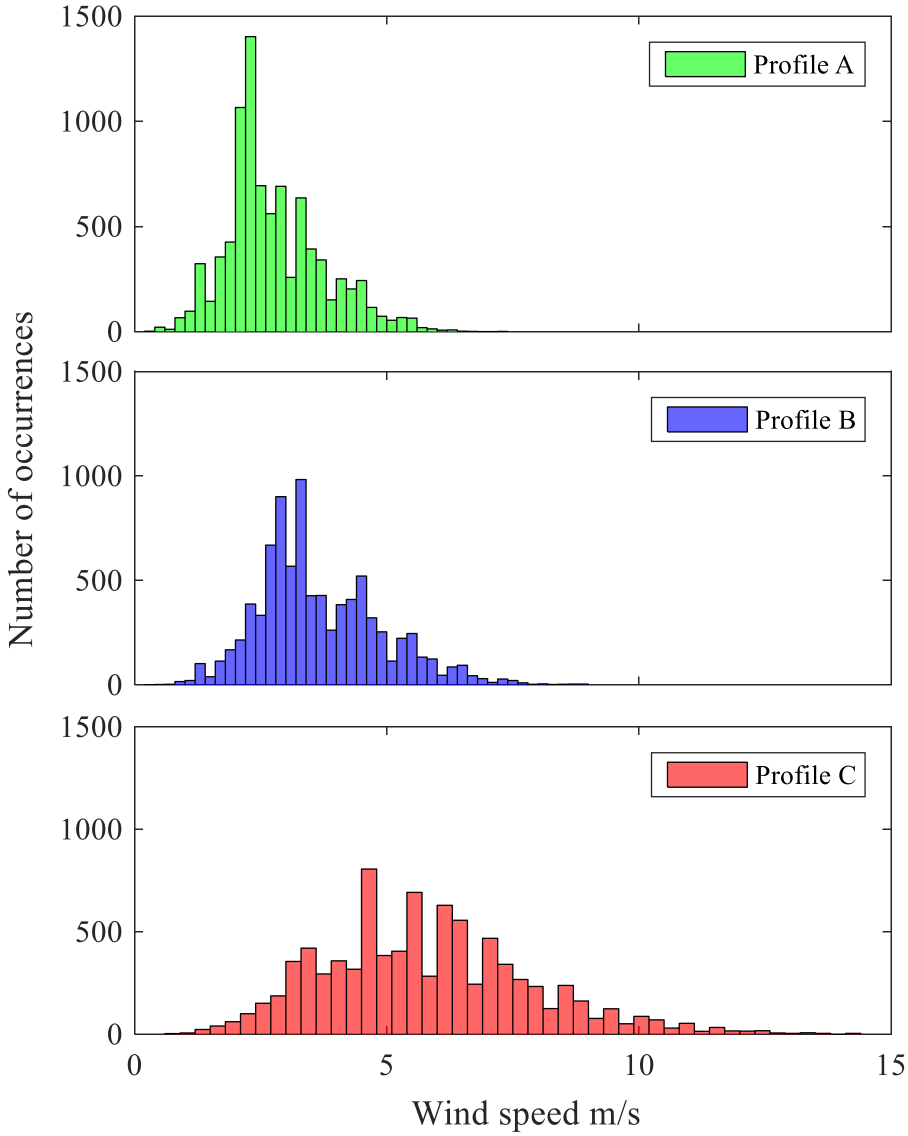

Figure 34 - Occurrences of hourly average wind speeds for the year, for all profiles.

By reviewing the number of occurrences of each wind speed for the case studies, we can determine what key aspect if the best solution for improving the effectiveness of a wind turbine. For profile A, the data shows that the wind speeds are focused mainly between 2 and 3 $m.s^{-1}$. Knowing this, a wind turbine would have to be able to output its rated power at these low speeds and have a cut-in speed even lower, which with current technology is not possible. For profile B, the bulk of the wind speeds occur at value over 3 $m.s^{-1}$, having a turbine with a cut-in speed of 1.5 to 2 $m.s^{-1}$, and a rated wind speed of 4 to 5 $m.s^{-1}$, would be a perfect fit for locations with this profile. For profile C, the available wind speeds are already favorable. Nevertheless, a turbine with a lower rated speed would be able to more effectively harness the potential power of the wind in the 3 to 5 $m.s^{-1}$ range.

Keeping the current and future technology in mind, to determine possible cost limitations of wind turbines, a study was conducted to analyze the behavior of an ideal wind profile. Using the daily potential power generated by the system, the same methodology was applied as with the generic turbines to determine the amount of useful energy and obtain the data for the payback projection of these ideal turbines.

For profile A, the payback is nearly as long as the turbines lifetime (20 years). With the same swept area of a 3kW turbine, a renewable fraction of at most 30% is attainable. However, to have an acceptable payback period of 7 years, a 3kW turbine system (3350€) would have to cost the same as a 1kW solar thermal collector (1200€). A 65% decrease in the cost of the turbines would be necessary across the board for locations with this profile to be financially viable, with an ideal turbine. In the current market this is not possible, therefore a wind application is, once again, not recommended for locations with this wind profile.

For profile B, a payback period of 6 years and a renewable fraction from 30 to 60% can be accomplished with the ideal turbine. Here, the turbine could stand to be less efficient if the price point of the system was lower, however, this would also diminish the renewable fraction. Therefore, if the goal is to maintain the renewable fraction and payback time, the only possible solution is to lower the cost of the turbine by 30 to 40%.

Finally, profile C already presented acceptable payback, 5 to 7 years, with the simulated generic wind turbine, which depending on the rated power, can reach 40 to 70% renewable fraction. With results such as these the situation is optimistic as it stands. If the turbine was ideal, the payback would range from 2 to 6 years, with a renewable fraction of 77 to 90%, and the cost of the turbine could even be increased. Despite this, it is always necessary to improve upon the technology and strive for a lower cost of renewable systems.

Assuming that the acceptable payback period for consumers falls between 5 and 7 years, this indicated that the locations that could benefit the most from wind turbine improvements are the ones with profile

B. Even with an ideal turbine, profile A still falls short of the demand and payback, therefore manufacturing technology that could be cost-effective for this profile would be difficult. For profile B, the main issue is the cut-in speed and secondly the rated wind speed, therefore, prioritizing a wind turbine with lower functioning speeds could still make this profile viable. For profile C, the cut-in speed and cost is viable as it stands, however, having a lower cost to implement the wind power system would make the technology have a higher market penetration.

Chapter 5 – Conclusion

5.1 Wind vs Solar

When comparing wind and solar power, for the case studies, we conclude that both profiles A and B cannot, currently, replace solar thermal collectors with the commercially available wind turbines. However, for profile C, the cost of renewable wind power, per kWh, was lower than solar power. The implementation of wind turbines proved to be less effective than expected for profiles A and B.

As for a possible hybrid system, the daily profiles of both resources present a similar behavior and so are not complementary throughout the day. However, concerning wind profile C and solar profile B, throughout the year, the wind and solar radiation balance have some correlation and can be a good combination for a hybrid system to be installed.

Overall, solar technology is already well implemented, nevertheless, with the advances of wind power, new wind turbines could surpass the capacity of the collectors in certain locations, specifically with profiles similar to case study B, and C.

5.2 Principal conclusions and future work

During the course of this dissertation, data was gathered for three distinct wind and solar profiles: Profile A (comparable to Aveiro), Profile B (comparable to Nazaré) and Profile C (comparable to Angra do Heroísmo). After the climate data was properly analyzed, two distinct models were used to simulate the hourly power output of a wind turbine and a solar thermal collector during an entire average year based on data from 1971 to 2000. After the simulations, the data was processed to obtain the daily, monthly and yearly data for the case studies. The results showed that it is possible to implement small scale wind turbines in an urban scenario in location with a high wind profile such as profile C. Locations similar to profile A, even when considering an ideal turbine, do not present the wind power availability that allows a cost-effective implementation of a small wind turbine. Therefore, for wind profiles like the one represented by profile A, small wind will not be financially viable. When compared to other renewable options, wind power can be viable at the current technological standpoint, both energetically and financially, although only in locations where the wind resource is high, such as profile C. The implementation of a hybrid system also proves to be advantageous, since the wind speeds peak in the winter and are at their lowest in the summer, with solar radiation peaking in the summer. The advantage being the system achieves up to 75% renewable fraction for water heating, with a payback period of 6 years, in sites with wind profile C combined with solar profile B.

Ultimately, wind power can be implemented at the urban scale with payback periods which, in the best case scenario, are comparable to most household solar thermal collectors. A lower cost of wind power can be obtained in the right location, with costs close to those of natural gas. This allows for renewable power or higher renewable fractions by installing these systems in regions which lack abundant solar resources.

This dissertation provides significant future research opportunities, as well as a solid argument for wind power investments and energy policies. This can be evidenced by profile B, as it represents locations where wind power can be viable by improving the technology. The study can aid research into this technology by providing an overall characterization of small wind in an urban scenario. Lowering the cut-in speed and increasing the efficiency of the components is a constant presence in the literature. It is also crucial to keep experimenting with new materials. Furthermore, we believe that by manufacturing a wind turbine that is made specifically for the purpose of water heating, with a more simplistic design, the cost of the turbine system can be much lower that it is in the current market. With the increasing research into new wind turbine technologies, the implementation of the system can become more widespread and accepted as a viable stand-alone renewable system.

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Appendix 1 – Altered monthly wind speed averages

The following tables show the impact of the changes to the wind speeds on the average monthly wind speed for the locations of Nazaré and Angra do Heroísmo.

Table 12 - Original and altered monthly wind speed averages, and the impact of the changes on the average wind speed (%), for Nazaré.

Month	Original Averages [m/s]	New Averages [m/s]	Nazaré Difference [%]
January	2.96	3.44	16.27
February	3.27	3.74	14.37
March	2.86	3.41	19.30
April	3.19	3.83	20.00
May	3.17	3.88	22.42
June	3.34	3.89	16.61
July	3.94	4.19	6.45
August	2.62	3.63	38.63
September	3.00	3.40	13.44
October	2.96	3.53	19.28
November	3.18	3.40	6.82
December	3.22	3.74	16.27

Table 13 - Original and altered monthly wind speed averages, and the impact of the changes on the average wind speed (%), for Angra do Heroísmo.

Month	**Original Averages [m/s]**	**New Averages [m/s]**	**Angra do Heroísmo Difference [%]**
January	6.25	7.06	12.97
February	6.56	7.49	14.22
March	6.32	7.13	12.85
April	5.46	6.19	13.31
May	5.57	6.11	9.61
June	3.60	4.44	23.40
July	3.27	4.00	22.43
August	4.17	4.57	9.57
September	4.45	5.20	16.75
October	4.80	5.58	16.21
November	5.21	6.25	19.99
December	4.50	5.95	32.16

Appendix 2 – Power results

The following figures present the power output of the simulated wind turbine and solar thermal systems from the SAM and HOMER Energy models.

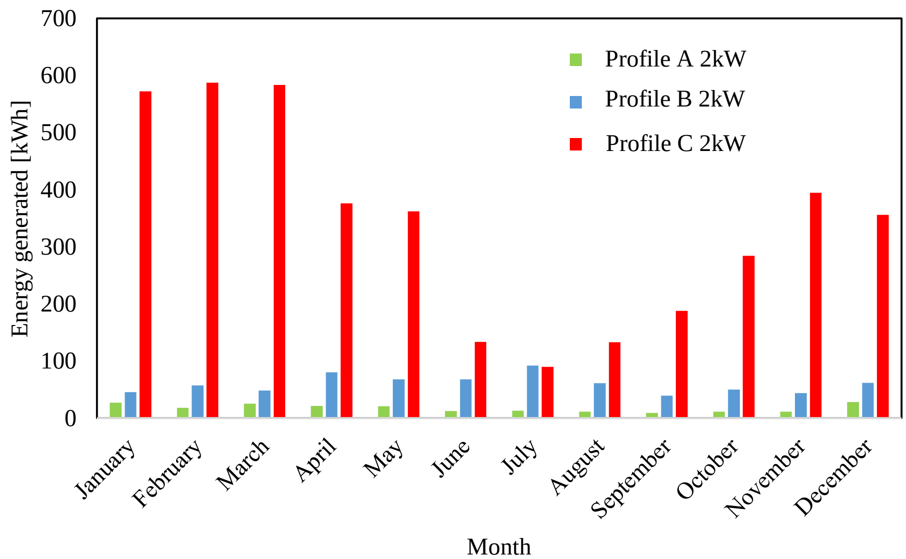

Figure 35 - Total energy generated, by a 2kW wind turbine for each profile and every month of the year (results from SAM simulations).

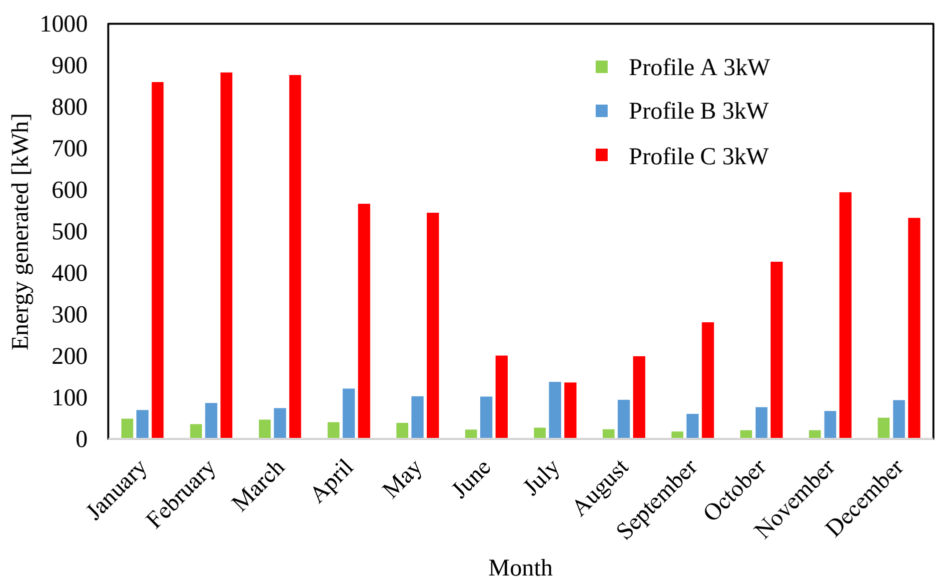

Figure 36 - Total energy generated, by a 3kW wind turbine for each profile and every month of the year (results from SAM simulations).

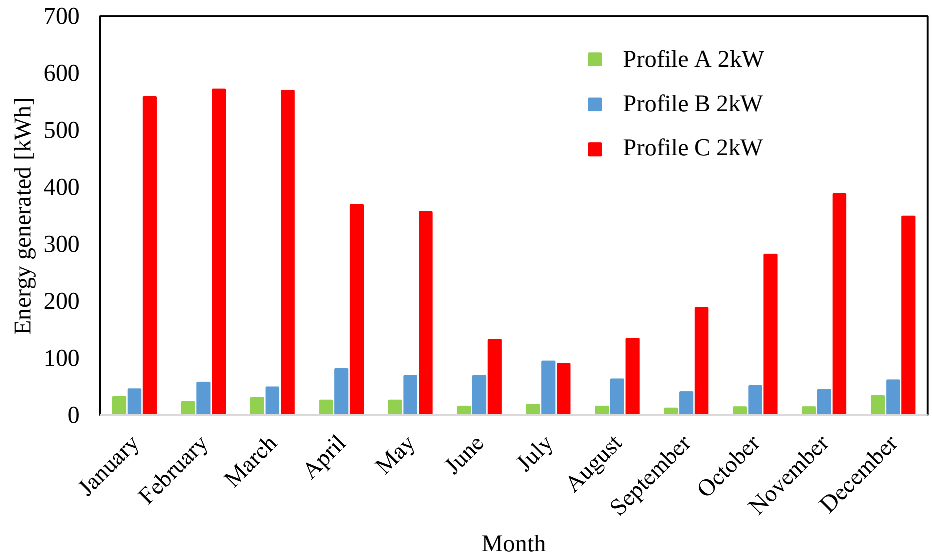

Figure 37 - Total energy generated, by a 2kW wind turbine for each profile and every month of the year (results from HOMER simulations).

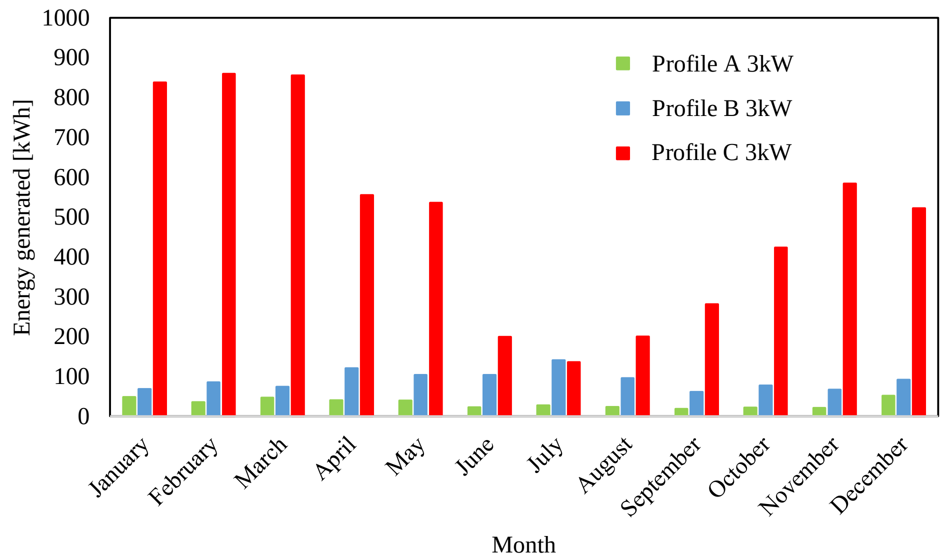

Figure 38 - Total energy generated, by a 3kW wind turbine for each profile and every month of the year (results from HOMER simulations).

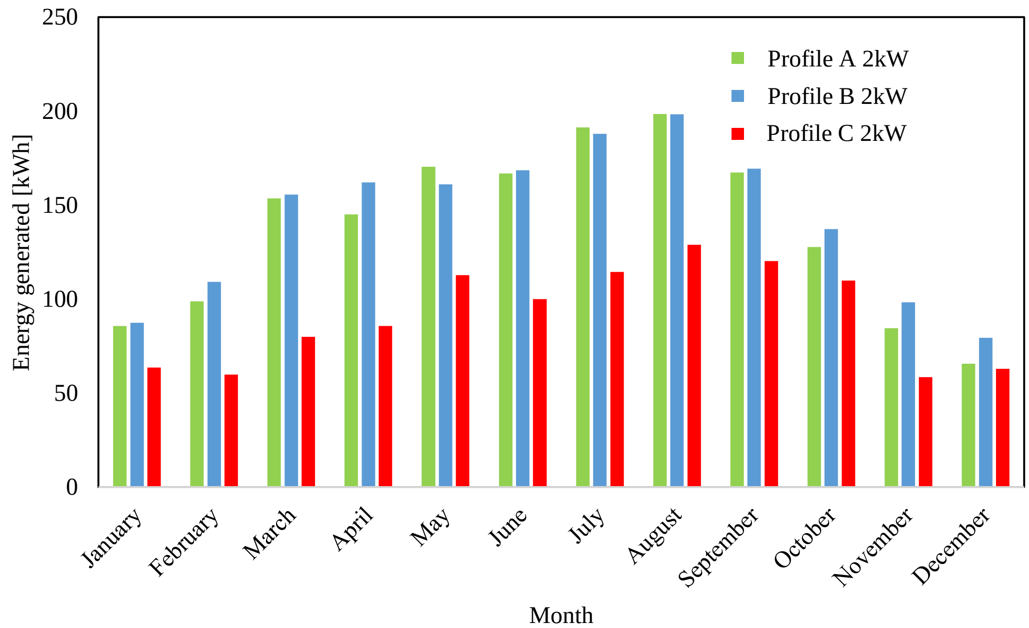

Figure 39 - Total energy generated, from a 2kW solar thermal collector for each profile, for every month of the year (results from SAM simulations).

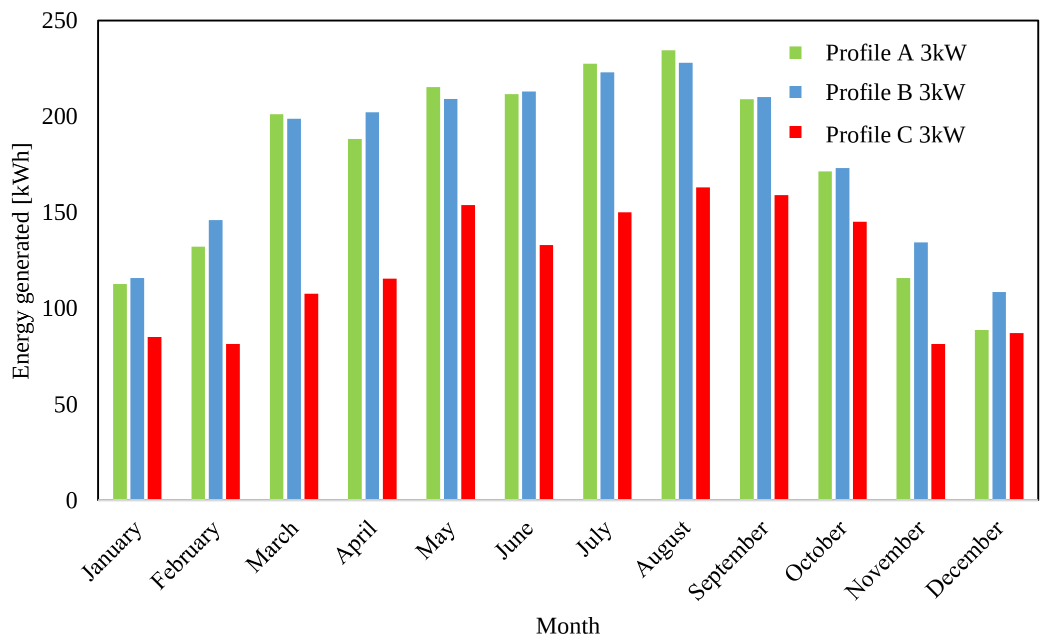

Figure 40 - Total energy generated, from a 3kW solar thermal collector for each profile, for every month of the year (results from SAM simulations).

Appendix 3 – Financial results

The following figures present the payback projection period for the wind turbines in profile A and B for both the SAM and HOMER models.

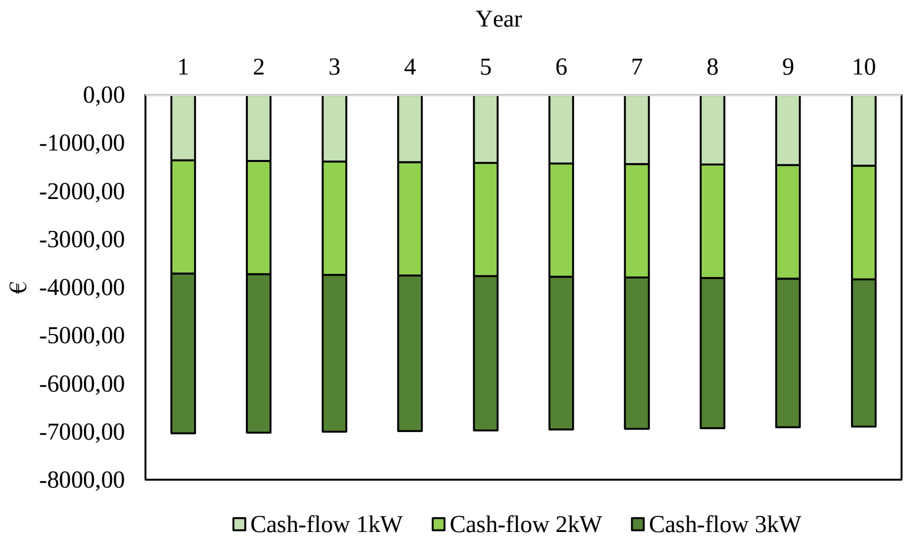

Figure 41 - Payback projection for all the wind turbines for profile A, based on the SAM model results.

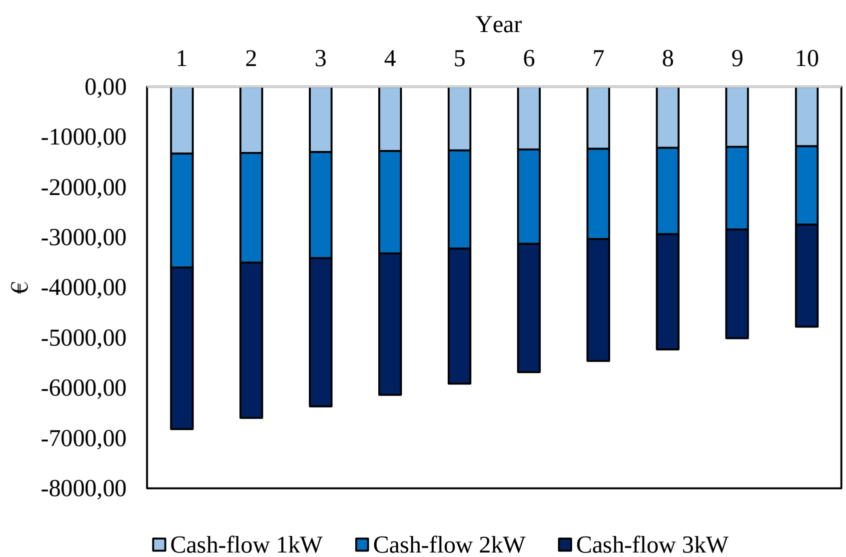

Figure 42 - Payback projection for all the wind turbines for profile B, based on the SAM model results.

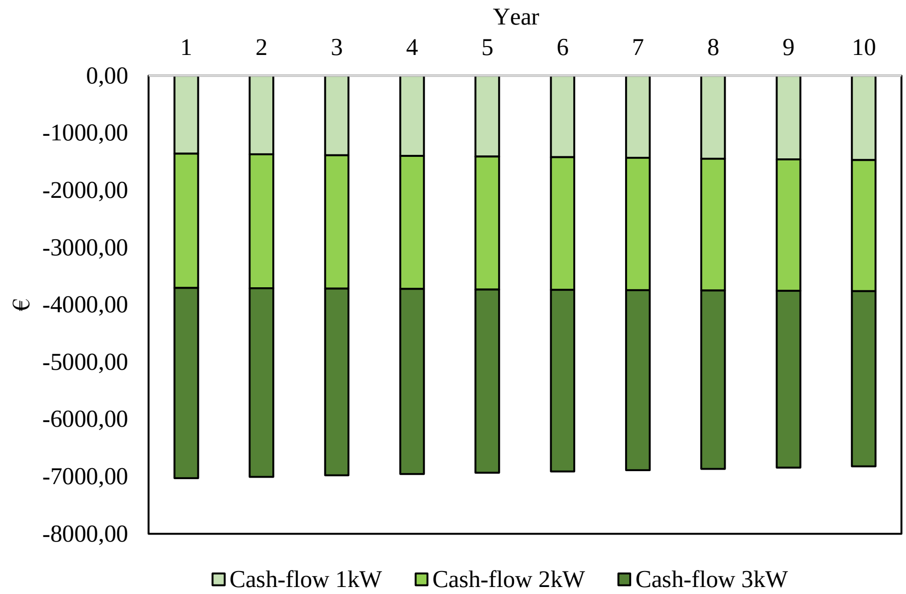

Figure 43 - Payback projection for all the wind turbines for profile A, based on the HOMER model results.

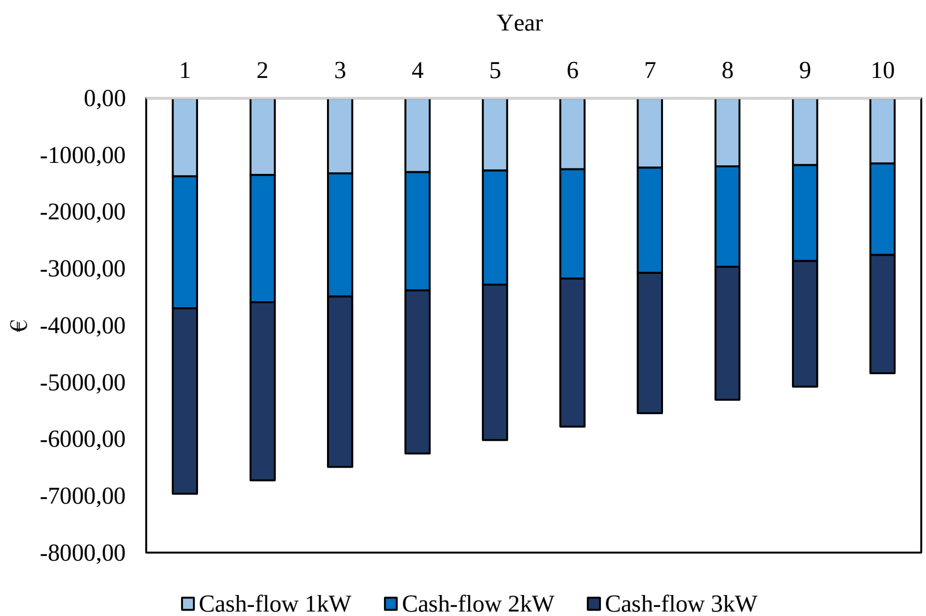

Figure 44 - Payback projection for all the wind turbines for profile B, based on the HOMER model results.